EXPLORING WATER FLUXES FOR AGRICULTURAL PRODUCTION IN AFRICAN CROPLANDS

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To my dear mother, and all those pursuing freedom, justice, and dignity

“Where can I free myself of the homeland in my body?”

– *Mahmoud Darwish*

Declaration

Ich versichere, dass ich diese Arbeit selbständig verfasst habe, keine anderen Quellen und Hilfsmaterialen als die angegebenen benutzt und die Stellen der Arbeit, die anderen Werken dem Wortlaut oder dem Sinn nach entnommen sind, kenntlich gemacht habe. Die Arbeit hat in gleicher oder ähnlicher Form keiner anderen Prüfungsbehörde vorgelegen.

Bonn, 10.04.2024
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Abstract

The deteriorating status of water scarcity and food insecurity poses a global challenge, driven by population growth, rapid urbanization, socio-economic developments, shifting consumption patterns, inefficient resource use, and climate change impacts. Agriculture, the largest user of freshwater and land resources, faces constraints due to diminishing availability of both blue and green water resources, leading to food shortages and increased vulnerabilities, particularly in Africa's developing regions. Recent trends in Africa show expansions in both rainfed and irrigated croplands. However, agricultural extensification strategies can disrupt ecosystems and biodiversity, notably in targeted floodplain wetlands, and exacerbate competition for scarce blue water resources, especially in arid regions and transboundary river basins. This thesis underscores the pressing need for agricultural intensification, emphasizing the enhancement of productivity on existing croplands.

The aim of this research is to identify and quantify the potential for increasing crop yields while conserving water and land resources across diverse agricultural systems in Egypt, Sudan, Ethiopia, and Tanzania. Additionally, this research aims to provide insights into the implications of potential improvements for future crop intensification and the associated demand for water and land resources. To achieve these multidisciplinary aims in such data-scarce regions, this research has developed novel methodological approaches. These approaches integrate open-access remote sensing datasets and secondary data to accurately monitor agricultural systems and associated parameters including land use, land cover, precipitation, actual and potential evapotranspiration, crop yield, and crop transpiration.

This thesis has demonstrated how these transferrable methodological approaches offer in-depth insights into the performance of agricultural systems, by calculating performance indicators including water use efficiency, crop water productivity, land productivity, evaporative stress, relative evaporative stress, and transpiration fraction, at adequate spatial and temporal resolutions across regions of diverse agricultural types, scales, and challenges. The spatial-temporal investigation conducted, covering sufficient timespans and spatial extents, proved instrumental in detecting spatial and temporal variabilities in performance indicators, thus enabling a reliable understanding of current performance status and facilitating the detection and quantification of potential improvements. These identified improvements have been used to construct plausible scenarios of future crop intensification and associated water and land requirements. Furthermore, the analyses conducted have identified specific interventions necessary to enhance production efficiency and to conserve water and land resources across the studied regions.

The findings of this thesis emphasize the considerable potential for crop intensification in the studied regions. The identified improvements have profound implications for water and food securities as well as for the sustainable development of water and land resources. These findings serve as pivotal entry points for guiding interventions and investments to enhance crop production and conserving vital water and land resources. These insights are valuable for strategic decision-making, directing efforts towards fostering agricultural sustainability and resilience amidst evolving environmental and socio-economic challenges.

Zusammenfassung

Wasserknappheit und Ernährungsunsicherheit stellen globale Herausforderungen dar, welche durch Bevölkerungswachstum, schnelle Urbanisierung, sozioökonomische Entwicklungen, veränderte Konsummuster, ineffiziente Ressourcennutzung und Auswirkungen des Klimawandels verursacht werden. Die Landwirtschaft, der größte Nutzer von Süßwasser- und Landressourcen, ist aufgrund der abnehmenden Verfügbarkeit sowohl blauer als auch grüner Wasserressourcen mit Einschränkungen konfrontiert, was insbesondere in vielen Regionen Afrikas zu Nahrungsmittelknappheit und erhöhter Anfälligkeit für Produktionsausfälle führt. Jüngste Trends in Afrika zeigen eine Ausweitung sowohl der regenabhängigen als auch der bewässerten Ackerflächen. Insbesondere in Feuchtgebieten trockener Regionen können solche Landnutzungsstrategien Ökosysteme und Biodiversität beeinträchtigen, und die Konkurrenz um knappe blaue Wasserressourcen verschärfen. Die vorliegende Arbeit unterstreicht die dringende Notwendigkeit für landwirtschaftliche Intensivierung in Form einer Steigerung der Produktivität auf bestehenden Ackerflächen.

Ziel dieser Forschung ist es, das Potenzial zur Steigerung der Ernteerträge bei gleichzeitiger Schonung der Wasser- und Landressourcen in verschiedenen Agrarsystemen in Ägypten, Sudan, Äthiopien und Tansania zu identifizieren und zu quantifizieren. Darüber hinaus soll diese Forschung Einblicke in die Auswirkungen möglicher Verbesserungen der Wassernutzung auf die künftige Anbauintensivierung und den damit verbundenen Bedarf an Wasser- und Landressourcen liefern. Um diese multidisziplinären Ziele in solchen datenarmen Regionen zu erreichen, wurden neuartige methodische Ansätze entwickelt, welche frei zugängliche Fernerkundungsdatensätze und Sekundärdaten integrieren, um die Landnutzung und Landbedeckung, sowie Niederschlag, tatsächliche und potenzielle Evapotranspiration und Ernteerträge in verschiedenen landwirtschaftliche Systeme abzuschätzen.

Die vorliegende Dissertation konnte zeigen, das die übertragbaren methodischen Ansätze detaillierte Einblicke in die Leistung landwirtschaftlicher Systeme bieten. Hierfür wurden Leistungsindikatoren wie Wassernutzungseffizienz und das Verhältnis von Transpiration zu tatsächlicher Evapotranspiration herangezogen um mit angemessener räumlicher und zeitlicher Auflösung die Wasser- und Landproduktivität in verschiedenen Regionen, bei unterschiedlicher Landnutzung und auf unterschiedlichen Skalenebenen zu berechnen und deren Variabilitäten zu bestimmen. Das verbesserte Verständnis des aktuellen Leistungsstatus ermöglicht somit die Erkennung und Quantifizierung möglicher Verbesserungen in der Wassernutzung. Diese erwiesen sich als wertvoll, um plausible Szenarien für die zukünftige Intensivierung des Anbaus und den damit verbundenen Wasserbedarf zu entwickeln. Darüber hinaus haben die durchgeführten Analysen spezifische Interventionen identifiziert, die zur Steigerung der Produktionseffizienz und zur Schonung der Wasser- und Landressourcen in den untersuchten Regionen erforderlich sind.

Die dargelegten Ergebnisse unterstreichen das erhebliche Potenzial für eine Intensivierung des Anbaus in allen Untersuchungsregionen, mit tiefgreifenden Auswirkungen auf die Wasser- und Ernährungssicherheit sowie auf die nachhaltige Entwicklung der Wasser- und Landressourcen. Diese Erkenntnisse dienen als zentrale Ansatzpunkte für richtungsweisende Interventionen und zielgerichtete Investitionen zur Verbesserung der Pflanzenproduktion bei gleichzeitiger Schonung der Wasser- und Landressourcen. Die Erkenntnisse können somit als Entscheidungshilfe dienen, um die Nachhaltigkeit in der Landwirtschaft zu fördern.

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θ	Moisture Content
AET	Actual Evapotranspiration
AGB	Aboveground Biomass
AoT	Aboveground over Total Biomass
BCM	Billion cubic meters = cubic kilometer
CAPMAS	Central Agency for Public Mobilization and Statistics
CBS	Central Bureau of Statistics
CGLS-LC	Copernicus Global Land Service Land Cover
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CSA	Central Statistical Agency
CV	Coefficient of Variation
CWP	Crop Water Productivity
ENC	Eastern Nile Basin Countries
ESA-CCI	European Space Agency Climate Change Initiative
ESI	Evaporative Stress Index
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Statistics
FEWS NET	Famine Early Warning Systems Network
g	Gram
$g\ C\ m^{-2}$	Gram carbon per square meter
$g\ C\ mm^{-1}$	Gram carbon per mm
$gC/m^2/day$	Grams of carbon per square meter per day
GDP	Gross Domestic Product
GFSAD	Global Food Security Analysis-Support Data
GIS	Geographic Information System
ha	Hectare
HAD	High Aswan Dam
HI	Harvest Index
kg	Kilogram
kg DM/ha/day	Kilograms of dry matter per hectare per day

kg/m^3	Kilogram/cubic meter
Kilombero	Kilombero Valley Floodplain
km	Kilometer
km^2	Square kilometer
km^3	Cubic kilometer = billion cubic meters
LUE	Light Use Efficiency
LUE_c	Light Use Efficiency correction factor
m^3	Cubic meter
m^3 cap^{-1}	Cubic meter per capita
m^3 ton^{-1}	Cubic meter per ton
Mha	Million hectare
MJ	Mega joule
mm	Millimeter
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NPP	Net Primary Production
P	Precipitation
PET	Potential Evapotranspiration
RES	Relative Evaporative Stress
SGDs	Sustainable Development Goals
SRTM	Shuttle Radar Topography Mission
SSA	sub-Saharan Africa
SSEBop	Operational Simplified Surface Energy Balance
T	Transpiration
T/AET	Transpiration fraction
t/ha	Ton/hectare
USGS	United States Geological Survey
WaPOR	FAO portal to monitor Water Productivity through Open access of remotely sensed derived data
WFP	Water Footprint
WUE	Water Use Efficiency

1. General introduction

1.1. Background

The current state of water scarcity and food insecurity remains a critical global concern. About 30% of the world's population live under moderate and severe levels of food insecurity (FAO, IFAD, UNICEF, WFP & WHO, 2023), while 65% experience conditions of severe water scarcity for at least one month of the year (Mekonnen and Hoekstra, 2016). The deteriorating trend in water scarcity and food insecurity is expected to continue in the future, driven by population growth, rapid urbanization, socio-economic developments, changing consumption patterns, inefficient resource use, and the impacts of climate change (United Nations, 2023a).

Freshwater constitutes about 2.5% of the planet's total water. However, because almost all of this water is stored in glaciers, ice caps, and deep groundwater, only about 0.3% of the total freshwater is readily accessible for human consumption (Shiklamonov, 1993). Precipitation is the main source of freshwater on land, which subsequently contributes to form either "blue" or "green" water resources (Falkenmark, 2003). "Blue" water refers to surface water found in lakes, rivers, and aquifers; it represents about 35% of the precipitation over land, and it is directly available for human use. In contrast, "green" water constitutes about 65% of the precipitation water, and it is stored as moisture in soil's root zone; while being vital for plant growth, it is typically not considered being directly available for human consumption (Falkenmark and Rockström, 2010, 2006).

Blue water predominantly supports irrigated agriculture, while crop production under rainfed practices depends mainly on green water. Globally, irrigated agriculture accounts for about 70% of total blue (freshwater) withdrawals, and it is mainly used for crop production (Rost et al., 2008). On the other hand, crop production under rainfed conditions uses about 60% of the world's total utilizable green water resources (Schyns et al., 2019). Green water contributes 87% of the global water use in croplands, while the remaining portion of 13% sustains irrigated agriculture and is supplied by blue water sources (Liu and Yang, 2010).

Agriculture is not only the main user of global freshwater resources, but agricultural activities also occupy a major share of the terrestrial land area. Thus, crop-related activities are found on 38% of the global land surface, of which about one-third being occupied by cropland and two-thirds being used as permanent meadows and pastures for livestock grazing (FAO, 2023a). Among the cropland area, 80% is rainfed and only 20% is irrigated, however, the irrigated land area contributes 40% to total food produced worldwide (FAO, 2022).

As agriculture accounts for the largest share of freshwater being used globally, the scarcity of blue or green water resources will directly hamper crop production, a situation that is further aggravated by climate and land use change processes (Dinar et al., 2019; Huang et al., 2019). Water scarcity can consequently induce reductions in agricultural land productivity, shortages in food supply, surges in food prices, and thereby increasing vulnerability among populations, particularly in developing regions of Africa where agricultural productivity must improve to sustain livelihoods (Fitton et al., 2019; Jayne and Sanchez, 2021).

About 90% or African cropland is comprised of rainfed areas, located in sub-Saharan Africa, while on 10% of cropland is irrigated, mostly located in the Nile region (Xiong et al., 2017a). In response to the rapid population growth and associated increasing demands for food in Africa (Hall et al., 2017), major recent change trends comprise expansions of both rainfed and irrigated cropland areas (Brink and Eva, 2009; Potapov et al., 2022). However, such strategies of agricultural extensification can be problematic.

On the one hand, cropland expansion in sub-Saharan Africa implies the conversion of natural vegetation into cropland, mainly in the amply-available floodplain wetlands of the continent with high potential for crop production (Rebelo et al., 2010). These conversions, and associated disturbances of wetland ecosystems by anthropogenic interventions (Beuel et al., 2016), adversely impact wetland biodiversity and the provision of ecosystem services (Mandishona and Knight, 2022) and raise concerns for wetland conservation policy adjustments (Langensiepen et al., 2023). In addition, wetland conversion can alter both the timing and the magnitude of water fluxes (Sterling et al., 2013), potentially intensifying extreme submergence and drought events and ultimately endangering crop cultivation and food security. On the other hand, investments in irrigation infrastructure to expand irrigated cropland entails an increased use of already-scarce blue water resources. In certain regions such as the Nile Basin, expanding irrigated cropland would exacerbate the competition for blue water of the Nile River, potentially intensifying water conflicts among sectors and nations that rely on the river's water (Elsayed et al., 2022a).

Given the multiple concerns of both irrigated and rainfed land use intensification approaches, recently advocated strategies to improve food security prioritize enhancing the productivity of food production systems on existing croplands, commonly referred to as sustainable intensification, although the definition of the concept is debated (Godfray, 2015; Petersen and Snapp, 2015). In a broad sense, agricultural intensification implies increasing agricultural output per unit of input, while minimizing potential detrimental impacts (Godfray and Garnett, 2014; Pretty and Bharucha, 2014). This definition excludes land expansion and focusses on improving the use efficiency of existing agricultural land and water resources. Sustainable intensification can be assessed by efficiency indicators that relate the output generated or the crop yield to units of input resource such as land or water (Cassman and Grassini, 2020). Land productivity (weight of harvested crop per unit of land area harvested), water productivity (weigh of harvested crop per unit of water consumed), or its inverse water footprint (the total volume of freshwater used to produce crops) are recommended indicators to assess the sustainability of cropland uses (Hoekstra et al., 2011; Molden et al., 2003). With water being the major input resource in both irrigated and rainfed crop production systems, assessing the potential for sustainable intensification should thus be coupled with analyses of water availability. Such coupled investigation may not only help identifying areas with the potential to improve production efficiency in irrigated areas (i.e., increased crop yield and conserved water resources), it may also help detecting areas with the potential to increase crop production in low intensity systems based on available water resources in rainfed areas.

Quantifying the potential for such improvements will permit constructing plausible future scenarios of agricultural intensification and associated water and land requirements. Crucial for achieving this goal is a detailed spatial and temporal monitoring of agricultural systems and water availability. However, *in-situ* data are extremely scarce on the African continent, and available data do not suffice to explain prevailing spatial and temporal variations.

Recent developments in satellites and remote sensing techniques permit to accurately monitor agricultural systems (Fritz et al., 2019). A number of the satellite-based agricultural monitoring missions exist, which are operational, open-access through public-domain sources, and available for Africa (Nakalembe et al., 2021). Some of the common agricultural and meteorological parameters being monitored include actual and potential evapotranspiration, transpiration, precipitation, crop yield, biomass, and land use and land cover (Weiss et al., 2020). As a result, we can comprehensively investigate performance efficiency indicators such as land and water productivities as well as water availability patterns with an adequate spatial and temporal resolution over African cropland.

To this end, this research addresses the aforementioned challenges in case studies in East and North Africa, where such research is scarce despite the pressing demand for knowledge:

1) The Kilombero Valley in Tanzania, representing crop production in floodplain wetlands under rainfed conditions using green water;
2) The Nile Delta, depicting irrigated agriculture using blue water from the local to the national level in Egypt; and
3) The Eastern Nile countries (Egypt, Sudan, and Ethiopia), portraying irrigated and rainfed practices using both blue and green water resources in a transboundary context.

1.2. Research hypotheses and objectives

The potential of improving African crop production systems must be investigated in a quantitative manner that consider spatial-temporal dimensions. Moreover, quantifying potential improvements can help construct plausible future scenarios of crop intensification and project associated water and land requirements. This approach will also highlight geographical areas with high or low performance, thus enabling the pinpointing of areas and opportunities to enhance production efficiency and to conserve water and land resources in the future. Consequently, it is surmised that:

i. Open-access remote sensing datasets can support improving investigations on agricultural systems in data-scarce regions.
ii. A comprehensive spatial-temporal investigation of crop production systems will enable understanding the current performance status and detecting potential improvements.
iii. Quantifying potential improvements in crop production and water use systems can help construct plausible future scenarios of crop intensification and associated water and land requirements.
iv. The spatial-temporal analysis will permit pinpointing interventions to enhance production efficiency and to conserve water and land resources.

The overarching aim of this study was to use remote sensing data to detect opportunities to increase crop yield and conserve water and land resources across selected case studies of African cropland. Furthermore, the study aimed to provide insights into the implications of such improvements for future crop intensification and associated water and land demand. To test the above hypotheses, the following objectives were addressed:

i. Providing novel methodological approaches based on entirely open-access datasets to analyze agricultural systems in parts of East and North Africa.
ii. Exploring the potential of dry season cultivation using prevailing green water in the Kilombero floodplain wetland in Tanzania.
iii. Analyzing the potential improvements in crop production under irrigation practices in the Nile Delta in Egypt and implications for future water and land demands.
iv. Assessing the current performance of cropland in the Eastern Nile countries (Egypt, Sudan, and Ethiopia) and exploring future scenarios towards sustaining production in a transboundary context.

1.3. Thesis outline

This doctoral thesis is conceived as a cumulative thesis and consists of six chapters.

Chapter 1 - General introduction: this chapter provides a background on the topic as well as the research hypotheses and objectives.

Chapter 2 - General material and methods: this chapter explains the general material and methods used in this research.

Chapters 3, 4, and 5: these chapters represent empirical research findings from the three case studies based on journal articles published in international peer-reviewed journals. These articles were formatted to fit the style of this thesis.

Chapter 3 - The Kilombero Valley Floodplain in Tanzania: this chapter represents the case study of the Kilombero Valley Floodplain in Tanzania addressing the potential of maximizing crop production using available green water in floodplain wetlands.

Corresponding publication: **Ayyad, S.**, Karimi, P., Langensiepen, M., Ribbe, L., Rebelo, L.-M., Becker, M., 2022. Remote sensing assessment of available green water to increase crop production in seasonal floodplain wetlands of sub-Saharan Africa. Agricultural Water Management. https://doi.org/10.1016/j.agwat.2022.107712

Chapter 4 - The Nile Delta in Egypt: this chapter depicts the case study of the Nile Delta in Egypt investigating the potential for improved production efficiency using blue water and future implications for water and land requirements at the national level.

Corresponding publication: **Ayyad, S.**, Karimi, P., Ribbe, L., Becker, M., 2024. Potential improvements in crop production in Egypt and implications for future water and land demand. International Journal of Plant Production. https://doi.org/10.1007/s42106-024-00301-7

Chapter 5 - The Eastern Nile countries (Egypt, Sudan, and Ethiopia): this chapter represents the case study of the Eastern Nile countries analyzing the potential of sustaining future crop production using blue and green water and the associated demands for water and land in a transboundary context.

Corresponding publication: **Ayyad, S.**, Khalifa, M., 2021. Will the Eastern Nile countries be able to sustain their crop production by 2050? An outlook from water and land perspectives. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2021.145769

Chapter 6 - General discussion and conclusions: this chapter provides general discussion on the findings of this thesis as well as outlooks and general recommendations.

2. General material and methods

This research addresses issues of a multidisciplinary nature in data-scarce regions of Africa. Thus, there was a need to use and integrate several datasets of different types, as well as to develop novel methodological approaches to derive plausible results using these datasets, while addressing associated uncertainties and limitations.

A primary type of dataset used in this study is gridded remote sensing products based on satellite observations. This type of data can significantly assist in conducting the spatial-temporal investigation required to achieve the study objectives. A plethora of remote sensing approaches exist to estimate the parameters under investigation, e.g., crop yield, actual evapotranspiration, land cover, precipitation, among others, with different performance quality and accuracy (Blatchford et al., 2019; Karimi and Bastiaanssen, 2015). As a result, numerous remote sensing products are available with various spatial and temporal resolutions and time and geographical coverages. Table 2.1 summarizes the remote sensing datasets used in this study. These datasets were selected based on the following criteria:

- Free accessibility through web-based public-domain sources to foster knowledge democratization and to empower researchers, decision-makers, and communities to verify findings, reproduce results, and address pressing agricultural challenges.
- Having adequate spatial and temporal resolutions and coverages to serve the purpose of the study.
- The performance quality of the product over the specific study area.
- To the possible extent, the continuity of missions providing these datasets to allow for replication and operationalization.

To ensure adequate performance quality of used remote sensing products in the absence of ground-truth data over the region under investigation, the selected products were evaluated through (i) their reported performance in relevant literature covering the study region, or (ii) cross comparison of products against reference datasets before use. In order to reduce uncertainties associated with systematic over- or underestimates of certain products, some techniques were adopted such as relying on relative than absolute values and merging one product with another. All used remote sensing datasets were processed in the ArcGIS 10.7 software (ESRI, 2019).

Another type of secondary datasets used was the national statistics. This type of data is typically provided as time series including population and crop statistics such as crop yield, harvested area, and production at the national scale. Time series of population and crop statistics required to assess crop production and consumption patterns as well as to construct scenarios of future water and land requirements are available for almost all countries and territories in the globe (FAOSTAT, 2023; United Nations, 2023b). Additionally, some countries including Egypt, Sudan, and Ethiopia have their own national statistics agencies and these were also used in this study (CAPMAS, 2023; CBS, 2020; CSA, 2020). Further secondary data required for parts of the analysis were obtained from literature, e.g., the water footprint values for crops (Mekonnen and Hoekstra, 2011a).

Table 2.1. Remote sensing datasets used in this study. The original sources of these datasets can be found in the corresponding chapters where the product was used as indicated in the table.

Dataset	Product name	Spatial and temporal resolution	Time coverage	Chapter
Land cover	ESA-CCI	300 m; Annual	1992–present	3 & 5
Land cover	MCD12Q1	500 m; Annual	2001–present	3 & 5
Land cover	WaPOR	250 m; Annual	2009–present	3 & 5
Land cover	CGLS-LC	100 m; Annual	2015–2019	3
Land cover	GFSAD	30 m; Annual	2015	3
Land cover	ESA-CCI-S2	20 m; Annual	2016	3
Land cover/crop type	WaPOR	30 m; 10-day	2009–present	4
Potential evapotranspiration	MOD16A2GF	500 m; 8-day	2001–present	3
Actual evapotranspiration	MOD16A2GF	500 m; 8-day	2001–present	3
Actual evapotranspiration	WaPOR	250 m; 10-day	2009–present	3
Actual evapotranspiration	SSEBop	1 km; 10-day	2012–present	3 & 5
Actual evapotranspiration	WaPOR	30 m; 10-day	2009–present	4
Transpiration	WaPOR	30 m; 10-day	2009–present	4
Crop yield	WaPOR	30 m; 10-day	2009–present	4
Crop water productivity	WaPOR	30 m; 10-day	2009–present	4
Precipitation	CHIRPS	5 km; Annual	1981–present	5
Net primary productivity	MOD17A3	500 m; Annual	2000–present	5
Normalized difference vegetation index	MOD13Q1	250 m; 16-day	2000–present	3

As the aim was to detect potential improvements in crop production over cropland, the developed methodological approaches included spatial analyses of remote sensing datasets and statistical analyses of time series generated from these datasets. In these approaches, the first step was to detect the cropland extent using available land cover products, followed by spatial analyses of other parameters over the detected cropland. Statistical analyses of time series were conducted to quantify certain parameters and analyze patterns indicating the opportunities for crop intensification. In the case studies with national focus, i.e., Chapters 4 and 5, analyses of time series included crop consumption and production patterns to project future demand of water and land resources to sustain crop production.

3. The Kilombero Valley Floodplain in Tanzania

This chapter is published as:

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Abstract

Producing more food for a growing population requires sustainable crop intensification and diversification, particularly in high-potential areas such as the seasonal floodplain wetlands of sub-Saharan Africa (SSA). With emerging water shortages and concerns for conserving these multi-functional wetlands, a further expansion of the cropland area must be avoided as it would entail increased use of blue water for irrigation and infringe on valuable protected areas. We advocate an efficient use of the prevailing green water on the existing cropland areas, where small-scale farmers grow a single crop of rainfed lowland rice during the wet season. However, soil moisture at the onset of the rains (pre-rice niche) and residual soil moisture after rice harvest (post-rice niche) may suffice to cultivate short-cycled crops. We developed a methodological approach to analyze the potential for green water cultivation in the pre- and post-rice niches in the Kilombero Valley Floodplain in Tanzania, as a representative case for seasonal floodplain wetlands in SSA. The three-step approach used open-access remote sensing datasets to: (i) extract cropland areas; (ii) analyze soil moisture conditions using evaporative stress indices to identify the pre- and post-rice niches; and (iii) quantify the green water availability in the identified niches through actual evapotranspiration (AET).

We identified distinct patterns of green water being available both before and after the rice-growing period. Based on the analyses of evaporative stress indices, the pre-rice niche tends to be longer (~70 days with average AET of 20–40 mm/10-day) but also more variable (inter-annual variability >30%) than the post-rice niche (~65 days with average AET of 10–30 mm/10-day, inter-annual variability <15%). These findings show the large potential for cultivating short-cycled crops beyond the rice-growing period, such as green manure, vegetables, maize, and forage legumes, by shifting a portion of the nonproductive AET flows (i.e., soil evaporation) to productive flows in form of crop transpiration. A cropland area of 1,452 to 1,637 km^2 (53–60% of the total cropland area identified of 2,730 km^2) could be cultivated using available green water in the dry season, which shows the significance of such change for food security, livelihoods, and resilience of the agricultural community in Kilombero.

A wider application of the developed approach in this study can help identifying opportunities and guiding interventions and investments towards establishing sustainable intensification and diversification practices in floodplain wetlands in SSA.

3.1. Introduction

Population growth and economic development are resulting in increasing exploitation of water and land resources to produce more agricultural commodities, a challenge that is aggravating with climate change (Foley et al., 2011). There is an increasing trend in sub-Saharan Africa (SSA) of converting (semi-) natural vegetative land covers into cropland (Brink and Eva, 2009). This conversion alters the timing and the magnitude of hydrological fluxes (Sterling et al., 2013) and, together with climate change and variability (Kotir, 2011), may intensify extreme flooding and drought events. Thus, agriculture, the predominant form of livelihood in SSA, could be severely harmed by further declining the already-low crop yields (van Ittersum et al., 2016). With growing concerns for nature conservation, sustaining ecosystem services, and loss of irrecoverable carbon (MEA, 2005; Noon et al., 2021), the further conversion of natural ecosystems and vegetation covers for agricultural production must be restricted. At the same time, the alarming status of food insecurity and deteriorating livelihoods in SSA necessitates the need for more adequate food production systems (Sasson, 2012), adopting resilient strategies for sustainable intensification (Rockström et al., 2017) and diversification (Kremen et al., 2012) to increase food production with minimal impacts on the environment. In Africa, such strategies demonstrated substantial potential for sustaining future crop production (Ayyad and Khalifa, 2021), reducing the agricultural carbon footprint (Kuyah et al., 2021), and for achieving food security and improving livelihoods (Vanlauwe et al., 2014; Waha et al., 2018).

Besides providing valuable ecosystem services and being hotspots of biodiversity (McCartney et al., 2010), wetlands in SSA play a vital role in supporting peoples' livelihoods (Wood et al., 2013) and economic developments (Schuyt, 2005). On the other hand, indiscriminate conversion of wetlands to sites of production potentially leads to their ultimate destruction (Beuel et al., 2016), a trend that is likely to be exacerbated by climate change (Mitchell, 2013). This paper focuses on seasonal wetlands, located within relatively large floodplains with seasonal soil submergence by riverbank overflowing and, to a lesser extent, by lateral runoff from adjacent slopes (Sakané et al., 2011). Such floodplain wetlands cover an estimated area of 692,631 km^2, and are thus an enormous and largely untapped resource for future food production (Rebelo et al., 2010). In these wetlands, farmers typically grow one single crop of rainfed lowland rice during the wet/rainy season (GRiSP, 2013). Before and after the wet season, farming activities are limited by water availability and variability, and cropland areas are often left to fallow for the rest of the year (Balasubramanian et al., 2007). Whenever affordable, farmers strive to adopt irrigation by using blue water resources (water in rivers, lakes, and aquifers), thus ensuring a year-round water supply for continuous crop cultivation. However, irrigation is often restricted by physical and economic realities in SSA, e.g., long distances between fields and rivers (Rockström and Falkenmark, 2015), high initial investments costs (Inocencio et al., 2007), and the lack of access to appropriate irrigation technologies and improved agricultural inputs as well as to reliable markets and research support (Nakawuka et al., 2018), contributing to the typical failure of large irrigation projects to deliver promised benefits (Higginbottom et al., 2021). Nevertheless, there are numerous other opportunities to maintain the soil moisture at productive levels by increasing (i) water storage, e.g., through rainwater harvesting technologies (Biazin et al., 2012) and (ii) irrigation technologies, such as motor pumps, communal river diversion, and small reservoirs (Xie et al., 2014).

Precipitation is the source of freshwater, which can take two forms; blue water or green water (Falkenmark and Rockström, 2006). Herein, green water refers to the plant-available water stored in the root zone as a result of natural processes without human intervention, i.e., precipitation, natural drainage, and floodwater (Karimi et al., 2013). While blue water solutions are primarily needed for urban, industrial, and energy developments and require large investments, better management of the more decentralized, highly adaptable, and low capital-demanding green water solutions can immensely contribute to improving rainfed agricultural systems and thereby food security in SSA (Keys and Falkenmark, 2018). However, little is known about green water availability and variability and hence its potential for diversifying and intensifying the existing crop portfolio in floodplain wetlands in SSA.

This research analyzes opportunities for sustainably intensifying and diversifying crop production systems in the Kilombero Valley Floodplain in Tanzania (hereafter referred to as "Kilombero"), which is representative for many other seasonal floodplain wetlands in SSA (Rebelo et al., 2010). The conversion of floodplain wetlands into cropland reportedly altered the water balance components on the sub-basin scale (Näschen et al., 2018) and increased the frequency, durations, severity, and intensity of drought events in Kilombero (Wambura and Dietrich, 2020). With water availability and variability widely limiting crop production in Kilombero, farmers may adapt their cropping calendars and establish community-based irrigation schemes (only about 1% of the total rice area is irrigated) (Höllermann et al., 2021). Thus, cropping strategies should be designed to adapt to the complex dynamic of seasonal water availability.

We explored the potential of using green water stored in the soil profile for cultivating additional crops before the rice establishment (pre-rice niche) and after the rice harvest (post-rice niche). The former practice exploits early-season rainfall events that do not suffice for soil flooding and puddling, and the transplanting of rice, to grow short-cycled green manure and food crops (Senthilkumar et al., 2018). The latter practice is known as flood recession cropping, where residual soil moisture is used for growing crops after the harvest of rice when seasonal inundation recedes (Sidibe et al., 2016). The durations and locations of these cropping niches depend to a large extent on the onset, intensity, and duration of the early-season rains (pre-rice niche) and the amount and duration of available residual soil moisture (post-rice niche). To our knowledge, no studies are available assessing this green water availability and its variability in seasonal floodplain wetlands in SSA. Thus, we investigated the spatial-temporal availability and variability of green water beyond the wet season in view of designing and targeting crop diversification and intensification strategies with a special focus on the potential cropping niches before and after wetland rice cultivation.

Numerous relative and absolute indicators for the availability of green water exist (Schyns et al., 2015). In absolute terms, green water availability is defined as the available soil moisture for vapor flows and is quantified by means of the actual evapotranspiration (AET) (Rockström et al., 2009), while in relative terms, green water availability is expressed by soil moisture conditions at a given location relative to a normal (average) condition (Schyns et al., 2015). In this paper, AET refers to the total vapor flux to the atmosphere as evaporation from interception, transpiration, and soil evaporation. *In-situ* point-based measurements of AET and soil moisture are scarce across SSA and, where available, cannot fully explain the spatial variation over larger areas or the temporal variation between seasons and years. In contrast to the highly data-demanding hydrological models (Zhao et al., 2013), satellite-based observations — commonly referred to as remote sensing gridded products — provide derived information on AET and soil moisture at various spatial and temporal scales. However, the currently-operationalized soil moisture products with long temporal coverage have rather coarse spatial resolutions of 25–50 km (Peng et al., 2021), limiting their applicability to smaller scales of cropland areas such as smallholder rice farms. Moreover, the performance quality of different AET products varies by regions (Weerasinghe et al., 2020). Thus, there is a need for alternative approaches for estimating soil moisture conditions and green water availability at high spatial and temporal resolutions.

Our overarching goal was to develop a remote sensing approach to analyze patterns of green water availability and to identify the potential for dry season cultivation in seasonal floodplain wetlands, using Kilombero as a case study. Our methodological approach includes three objectives: (i) delineation of cropland areas; (ii) analyzing the dynamics of intra-annual soil moisture conditions across extracted cropland areas for a long time series and, thereby, identifying the pre- and post-rice niches; and (iii) quantifying and mapping AET in cropland areas with particular focus on the two so far unexploited cropping niches. This approach serves as a starting point towards exploring possible strategies for dry season cultivation in floodplain wetlands in and beyond Kilombero based on extensive spatial and temporal coverage provided by relevant remote sensing datasets. The outputs of these objectives can advance our understanding of the prospects of realizing the agricultural potential, improving the livelihoods of farming communities, and ultimately for achieving multiple sustainable development goals in seasonal floodplain wetlands of SSA.

3.2. Materials and methods

3.2.1. Kilombero wetland

The Kilombero Basin is located in south-central Tanzania, covering about 40,000 km^2 and contributing 62% of the annual runoff of the Rufiji River Basin (Wilson et al., 2017) (Fig. 3.1a). The basin has a tropical climate, with distinct dry (June–October), short (November–January), and long (March–May) rainy seasons (Koutsouris et al., 2016). The monthly average temperatures, precipitation, and solar radiation reflecting the seasonality in the basin are presented in Fig. 3.1b.

Covering an area of approx. 8,000 km^2, Kilombero floodplain is the largest lowland seasonal floodplain wetland in East Africa (Wilson et al., 2017). The unique ecological features and biodiversity have led to designating it as a Ramsar site in 2002 (Mombo et al., 2011). The ecosystem services supported by Kilombero floodplain, and in particular the provisioning services (Koko et al., 2020), are vital to the livelihoods of local communities (Rebelo et al., 2010). Rainfed lowland rice cultivation dominates the local activities during the rainy season (Gebrekidan et al., 2020), making Kilombero one of the largest rice-growing areas in East Africa that supplies 9% of Tanzania's national rice production (Kato, 2007). As a result of the intensifying human interventions, driven by population growth and the growing market demand and price incentives for agricultural products, a trend of converting natural vegetative land covers into rice cropland was observed in Kilombero, primarily to increase rice crop production and thus improving livelihoods (Kirimi et al., 2018; Msofe et al., 2019; Munishi and Jewitt, 2019; Thonfeld et al., 2020a, 2020b). Such land cover change represents a threat to the biodiversity (Seki et al., 2018) and the biophysical system of Kilombero (Muro et al., 2018). In addition, it can alter the inflow of several tributaries and the maintenance of environmental flow (Wilson et al., 2017), which are essential to sustain the ecosystem and the human livelihoods that are dependent on these ecosystems (Leemhuis et al., 2017). Yet, there is an enormous and largely untapped potential to increase rice production by closing the yield gaps on existing croplands in Kilombero without expanding the cropped area (Kwesiga et al., 2020a).

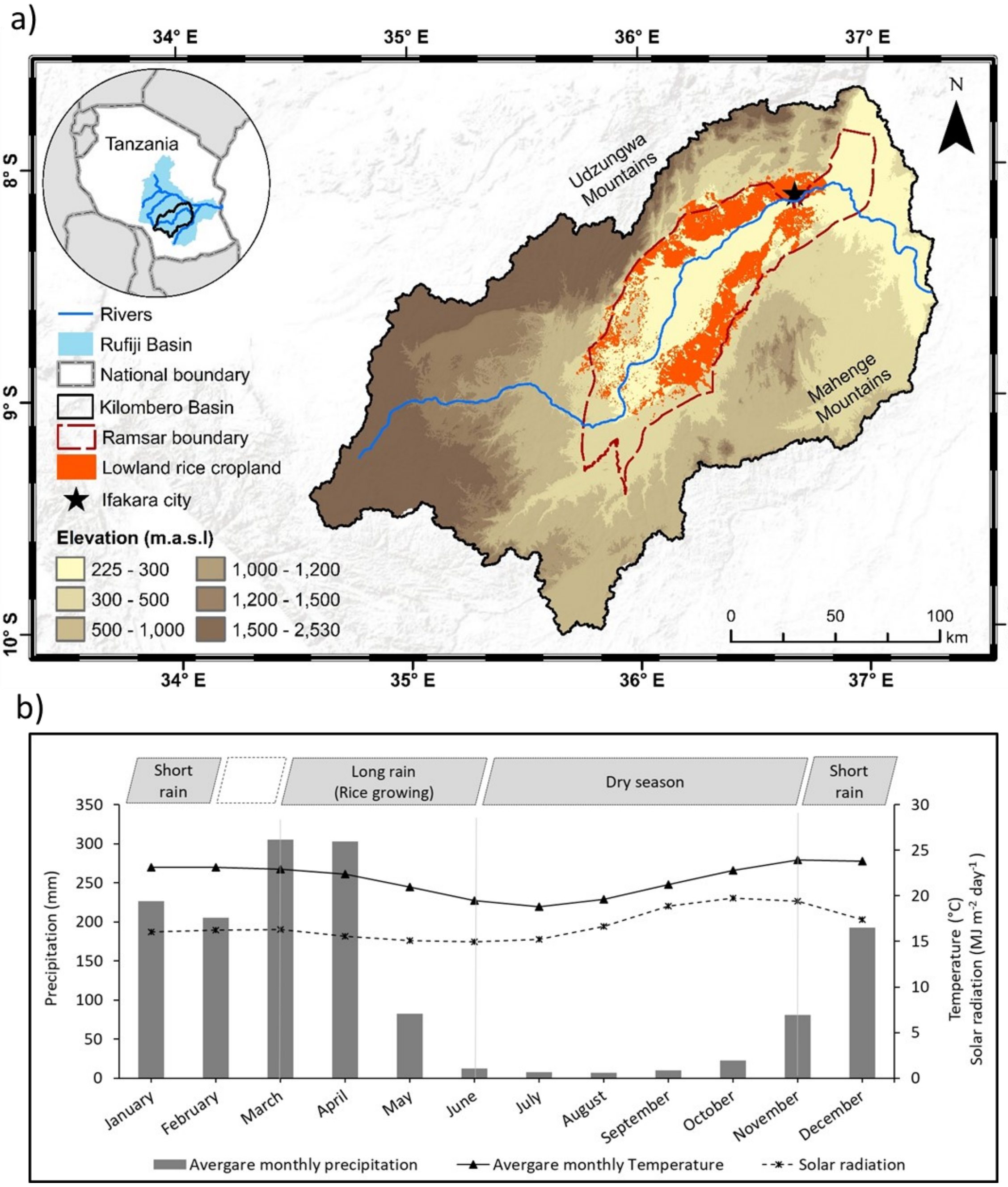

Fig. 3.1. a) Location map of the Kilombero Valley Floodplain. National boundary: https://www.naturalearthdata.com/, Rivers: http://landscapeportal.org/, Rufiji Basin: https://datacatalog.worldbank.org/, Kilombero Basin (delineated using the SRTM elevation: https://srtm.csi.cgiar.org/srtmdata/), Kilombero Ramsar boundary: https://www.protectedplanet.net/en, Cropland areas within Kilombero floodplain: FAO (2019). b) Average monthly precipitation, temperatures, and solar radiation over the Kilombero Basin for the period 1970–2000 (Fick and Hijmans, 2017).

3.2.2. Methodological approach

We investigated the potential of exploiting available green water resources to support dry season crop cultivation (Fig. 3.2). The proposed remote sensing-based approach comprises three steps: (i) evaluating multiple land cover datasets and identifying a reliable dataset to delineate the extent of croplands in Kilombero; (ii) estimating soil moisture stress and its variability by using the ratio of actual (AET) to potential evapotranspiration (PET); (iii) quantifying the green water availability by means of AET. The first step served as a basis for subsequent analyses because of the commonly-known disparities among land cover datasets in detecting the cropland extent (Pérez-Hoyos et al., 2017).

Fig. 3.2. The proposed methodological approach applied for assessing the green water availability and variability to support dry season cultivation in seasonal floodplain wetlands of sub-Saharan Africa. ESI: evaporative stress index, RES: relative evaporative stress, AET: actual evapotranspiration, PET: potential evapotranspiration, and NDVI: normalized difference vegetation index.

The second step assumes that AET under actual soil moisture conditions can reach an upper limit of PET, the latter represents the atmospheric evaporative demand when the soil water supply is unlimited (Xiang et al., 2020). This step is aimed at detecting the inter- and intra-annual soil moisture stress for long time series, in view of identifying the spatial and temporal boundaries of potential pre- and post-rice cropping niches. In addition, calculating the inter-annual variability of soil moisture stress permitted for understanding the risks and opportunities associated with different locations and periods during the identified niches. In the third step, we quantified green water for short timesteps (10-day) within the identified niches as well as for the full length of both niches. The periods and data mentioned in Fig. 3.2 were those used in the present study.

3.2.3. Gridded datasets

To achieve the study objectives in such a data-scarce region, we used open-access gridded datasets and GIS techniques, which are seen to be useful to monitor and manage wetlands effectively (MacKay et al., 2009; Rebelo et al., 2009). Herein, we used multiple datasets to delineate the cropland extent and explore the spatial-temporal patterns of soil moisture stress and AET (Table 3.1). These products were selected specifically because of their substantial temporal and spatial coverages, their free accessibility through public-domain sources, and their missions still operating to date, allowing for the operationalization and use of these products in future research. The required datasets were downloaded and processed in the ArcGIS environment (ESRI, 2019).

Table 3.1. Description of gridded datasets used in the present analysis (AET and PET refer to actual and potential evapotranspiration, respectively. NDVI refers to normalized difference vegetation index).

Dataset	Product	Spatial and temporal resolution	Downloading link
Land cover	ESA-CCI	300 m; Annual	https://www.esa-landcover-cci.org/
Land cover	MCD12Q1	500 m; Annual	https://lpdaac.usgs.gov/products/mcd12q1v006/
Land cover	WaPOR	250 m; Annual	https://wapor.apps.fao.org/home/WAPOR_2/1
Land cover	CGLS-LC	100 m; Annual	https://land.copernicus.eu/global/products/lc
Land cover	GFSAD	30 m; only 2015	https://www.croplands.org/home
Land cover	ESA-CCI-S2	20 m; only 2016	http://2016africalandcover20m.esrin.esa.int/
AET & PET	MOD16A2GF	500 m; 8-day	https://lpdaac.usgs.gov/products/mod16a2gfv006/
AET	WaPOR	250 m; 10-day	https://wapor.apps.fao.org/home/WAPOR_2/1
AET	SSEBop	1000 m; 10-day	https://earlywarning.usgs.gov/fews
NDVI	MOD13Q1	250 m; 16-day	https://lpdaac.usgs.gov/products/mod13q1v006/

3.2.4. Land cover analysis

Disparities have been reported and disagreements exist between different land cover datasets across Africa (Tsendbazar et al., 2015; Xu et al., 2019), especially when identifying cropland extents (Fritz et al., 2010; Nabil et al., 2020). Therefore, we compared four land cover datasets: (1) the European Space Agency Climate Change Initiative with 300 m spatial resolution (ESA-CCI; ESA, 2017); (2) the Terra and Aqua combined MODIS Land Cover dataset version 006 (500 m) (MCD12Q1; Friedl and Sulla-Menashe, 2019); (3) the FAO portal to monitor Water Productivity through Open-access of Remotely sensed derived data with a spatial resolution of 250 m (WaPORv2.1; FAO, 2018); and (4) the Copernicus Global Land Service Land Cover (CGLS-LC; Buchhorn et al., 2020) with a 100 m spatial resolution. Detailed information regarding the land cover classes of each product and their descriptions can be found in their cited references. Relevant classes were selected from each product to delineate the cropland extent (class numbers 10 and 20 from ESA-CCI, 12 and 14 from MCD12Q1, 41 and 42 from WaPOR, and 40 from CGLS-LC). After extracting the cropland classes from the four selected datasets across the rice cultivation area of Kilombero, we compared them with cropland layers extracted from another two land cover products with higher spatial resolutions, namely the Global Food Security Analysis-Support Data product (GFSAD; Xiong et al., 2017b) and the ESA-CCI-S2 prototype product, developed by the ESA-CCI land cover team (Table 3.1). GFSAD (30 m) and ESA-CCI-S2 (20 m) offer global and African cropland extents for the years 2015 and 2016, respectively, and have shown fair accuracies of approximately 93% and 65%, respectively, in identifying cropland extents across Africa (Lesiv et al., 2017; Yadav and Congalton, 2018). The land cover comparison followed two steps: (1) the visual assessment, here we cross-compared the cropland extent from the four evaluated products and against the corresponding cropland extents from GFSAD and ESA-CCI-S2, and (2) comparing the absolute area of detected cropland, here we estimated the cropland area from the short-listed datasets from step (1) and compared them with the cropland area estimated from GFSAD and ESA-CCI-S2. Based on these steps, one land cover product was selected and used in the subsequent analyses of soil moisture and AET.

3.2.5. Soil moisture conditions

The hydrology of seasonal floodplain wetlands is complex and determined by multiple factors, including the distance to the river, groundwater levels, soil properties, atmospheric demands, river overbank flow, direct precipitation, groundwater discharge, and lateral flow from surrounding mountains (Burghof et al., 2018; Gabiri et al., 2018). Thus, we studied the spatial and temporal patterns of soil moisture stress resulting from different hydrological processes, without investigating its underlying factors and sources. Multiple agricultural drought indicators are available, comparing the actual (AET) to the potential (PET) evapotranspiration as a proxy to estimate soil moisture conditions (Schyns et al., 2015). Among those, we selected the evaporative stress index (ESI), as it identifies areas with soil moisture stress based on the land surface dryness without requiring many meteorological inputs (Anderson et al., 2007). In fact, ESI is similar to other existing drought indicators (Schyns et al., 2015), namely the crop water stress index (Jackson et al., 1981), the water stress ratio (Narasimhan and Srinivasan, 2005), and the evaporative drought index (Yao et al., 2010). ESI is calculated as:

$$\mathrm{ESI} = 1 - \mathrm{AET}/\mathrm{PET} \tag{3.1}$$

ESI values vary between 0 and 1 and, according to Yao et al. (2010), they can be grouped as wet (ESI ≤0.2), normal (0.2< ESI ≤0.4), moderate (0.4< ESI ≤0.6), severe (0.6< ESI ≤0.8), and extreme dry soil moisture or drought (ESI >0.8). In the present study, ESI values of >0.7 were considered as the threshold for severe drought, indicating a level of water deficit hampering crop growth. The reason for shifting this threshold from 0.6 to 0.7 is that, ESI classification is based on its relationship with the 0–10 cm soil moisture (Yao et al., 2010), while crop roots can reach deeper soil profiles (until 50 cm depth) and therefore extracting more water for transpiration (Savenije, 2004) and hence having higher ESI values.

To understand the soil moisture conditions in the relative sense, the relative evaporative stress (RES) index, following ESI, is proposed. RES is calculated as follows:

$$\mathrm{RES} = \mathrm{CV}\,(1 - \mathrm{AET}/\mathrm{PET})_{\mathrm{i}} \times 100 \tag{3.2}$$

where $(1 - \mathrm{AET}/\mathrm{PET})$ is calculated for a long-term time series and can be calculated at various time steps (i) and CV is the coefficient of variation (calculated as the ratio of the standard deviation to the mean value). RES represents the degree of variation or stability in ESI time series (in %); the higher the RES (high variability), the less stable is the time series, and vice-versa. The index can be applied at various spatial and temporal scales. We used RES to detect the risks and opportunities associated with dry season cultivation. A RES value of 20%, for example, means that the ESI may deviate 20% from the long-term average ESI value, implying a high stability in the ESI time series in a specific location or pixel. Similarly, a 50% RES value indicate that ESI value may disperse by half of the long-term average ESI value, suggesting a highly unstable situation. Therefore, we decided to calculate RES following four classes; RES <20%, 20%< RES <30%, 30%< RES <40%, and RES >40%.

With our focus on the pre-and post-rice cropping niches, ESI and RES had to be calculated at the highest possible spatial and intra-annual temporal scales. Thus, we used the evapotranspiration remote sensing products of the Moderate Resolution Imaging

Spectroradiometer (MODIS; MOD16A2GF v006). The MOD16A2GF product compromises information on AET and PET based on the Penman-Monteith logic (Monteith, 1965) at 500 m spatial resolution and at 8-day timesteps. AET and PET were calculated over each cropland pixel and for each 8-day period throughout the year (46 [8-day] periods/year) for the entire available period of the products (2000–2019). We produced maps and time series of ESI and RES for each 8-day period (2000–2019).

3.2.6. Green water availability

As crop water requirements refer to the amount of water needed to meet the plants water losses (Brouwer and Heibloem, 1986), AET appears to be a suitable indicator to assess green water or soil moisture availability. Since measured values of AET only occur when/where there is water, AET can serve as a minimum threshold to soil water available for crop use. The inter-annual AET was analyzed with particular focus on the identified pre-and post-rice cropping periods with soil moisture conditions sufficient for growing crops. Among several AET products available, we used two products with high spatial and temporal resolutions, namely WaPOR (250 m, 10-day) and SSEBop (1000 m, 10-day), developed based on the concepts of ETLook (Bastiaanssen et al., 2012; Pelgrum et al., 2010) and operational Simplified Surface Energy Balance (Senay et al., 2013), respectively. Both products were evaluated in several regions and climatic zones across Africa, showing high performance estimating AET, e.g., over the hyper arid agricultural areas of Egypt (Ayyad et al., 2019), the Volta River Basin (Dembélé et al., 2020), the Nile River Basin (McNamara et al., 2021), and at continental scale (Blatchford et al., 2020; Weerasinghe et al., 2020).

We resampled the SSEBop product to the spatial resolution of WaPOR (250 m), using bilinear interpolation, and created an ensemble mean of their AET values for each pixel for the entire common period of the two products (2009–2020). The reason for creating this ensemble mean was because, despite their general good performance, WaPOR and SSEBop were reported to over- and under-estimate AET, respectively (McNamara et al., 2021; Weerasinghe et al., 2020). Furthermore, creating this ensemble mean of such well-performing products with different constructing concepts can propagate potential uncertainties in the results and make them more realistic (Zhang et al., 2016). Actual evapotranspiration estimates of the ensemble mean product were tested by correlating them to values of an independent vegetation index—the normalized difference vegetation index (NDVI). The latter has a strong correlation with AET and is commonly used to assess AET product performance. We used the NDVI product from MODIS (MOD13Q1 v006) with 250 m resolution and 16-day timestep (Didan, 2015). NDVI values below 0.1 correspond to non-vegetated surfaces (Gandhi et al., 2015) and were therefore masked out. Both the NDVI and AET ensemble mean products were compared on monthly basis (2009–2020) and a linear regression (using R^2) was applied to examine the correlation between the two datasets.

In our analysis, we used the ensemble product to estimate and map AET for each 10-day period from 2009 to 2020 to understand and quantify the soil water availability across time and space over Kilombero. AET was calculated with intervals of 10 (mm/10-day) to simplify the visualization and interpretation of AET values, for instance, AET of 30-40 mm/10-day can easily be interpreted to approximately 3-4 mm/day. Furthermore, for the identified pre- and post-rice niches, we calculated the aggregated AET for the entire duration of both niches to quantify the total water availability of these niches.

3.3. Results

3.3.1. Land cover

The land cover analysis revealed considerable disparities between products in capturing the extent of the cropland (Fig. 3.3). Compared to GFSAD and ESA-CCI-S2, the WaPOR and CGLS-LC products showed consistent agreement on the extent and spatial distribution of cropland (Fig. 3.3a–d). On the other hand, ESA-CCI partially miss-captured the extent of the cropland area (Fig. 3.3e), while nearly no cropland was identified in the selected layers from MCD12Q1 (Fig. 3.3f, marked in green), which classified cropland as savanna or grassland. Thus, MCD12Q1 and ESA-CCI were considered unsuitable to delineate cropland areas in Kilombero, which are nearly exclusively lowland rice. Cropland areas were also assessed for 2015 and 2016, yielding comparable results for WaPOR (2,730 km^2), CGLS-LC (2,320 km^2), GFSAD (2,515 km^2), and ESA-CCI-S2 (2,725 km^2). The cropland area estimated by WaPOR was nearly identical to that of ESA-CCI-S2 and compared well with that of GFSAD. Thus, we considered WaPOR to be the most reliable product for delineating (rainfed rice) cropland areas in Kilombero.

3.3.2. Soil moisture conditions

Distinct temporal patterns of dry and wet seasons in Kilombero result in a strong seasonality of soil moisture availability for crops as determined by the evaporative stress index - ESI (Fig. 3.4). ESI values of <0.2 indicate soil submergence, while values >0.7 indicate a level of water deficit hampering crop growth (Fig. 3.5). Wettest soil moisture conditions were detected during the main rainy season between late February and mid-May, also representing the lowland rice-growing period (Fig. 3.4 and 3.5). On the other hand, moderate soil moisture conditions that are potentially suitable for crop growth were observed during the pre-rice cropping niche between early January and mid-March as well as in the post-rice cropping niche between mid-May and late July.

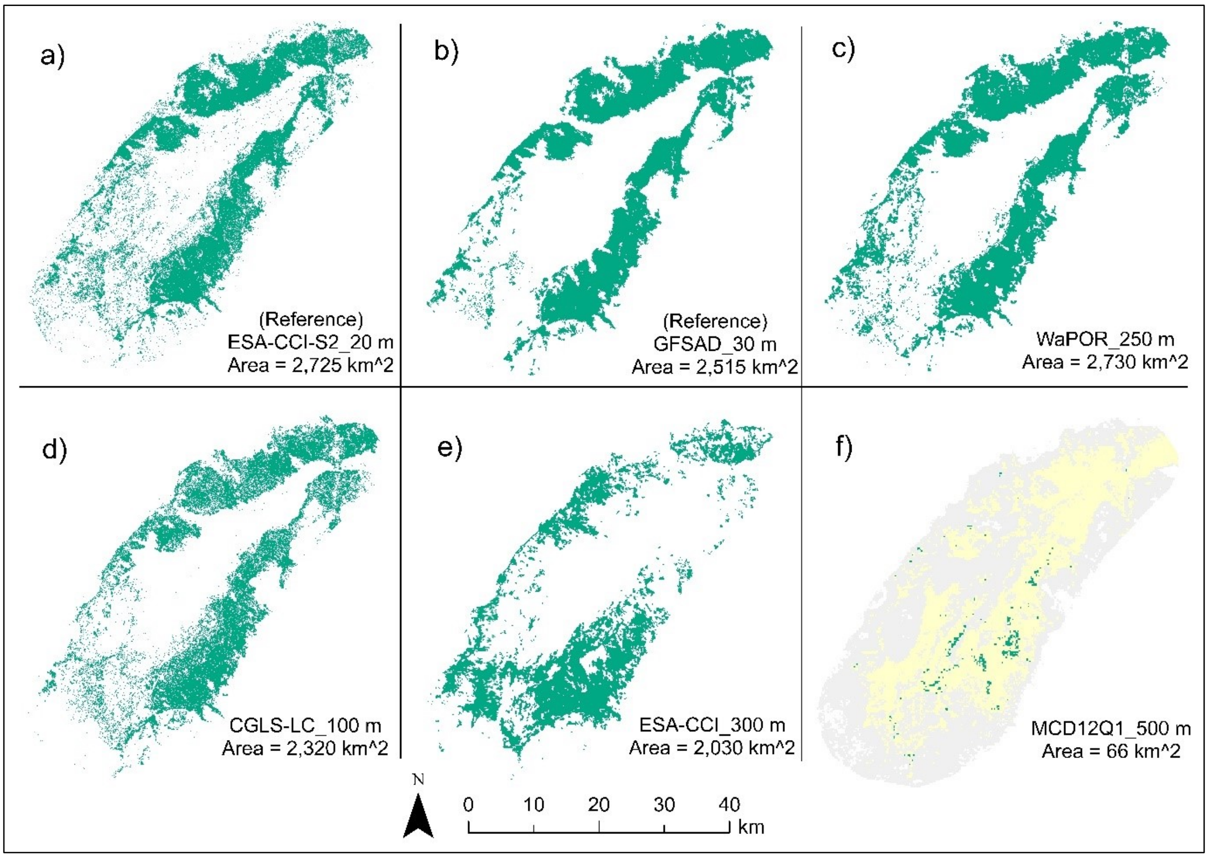

Fig. 3.3. Extent of the cropland area in Kilombero floodplain (Tanzania) as extract from a) ESA-CCI-S2 (2016), b) GFSAD (2015), c) WaPOR (2015), d) CGLS-LC (2015), e) ESA-CCI (2015), and f) MCD12Q1 (2015). Cropland layers from MCD12Q1 are presented by green pixels in panel f, with the background colors presenting savanna grassland.

Crop cultivation without supplemental irrigation is not feasible between early-August to mid-December as indicated by severe soil dryness (ESI >0.7). In consequence, potential niches for dry season crop cultivation occur (1) between mid-December and late February (approximately 70 days of soil moisture availability), representing the cropping niche before the transplanting of wetland rice in early March, and (2) between late May and late July (approximately 65 days of soil moisture availability), representing the cropping niche after the harvest of wetland rice in May.

Besides these temporal patterns, the stress index also highlights distinct spatial patterns. By the end of the post-rice niche (from 20th to 27th of July), we detected a total area of 1,452 km^2 with ESI of <0.7, representing 53% of the total cropland area in Kilombero. Similarly, an area of 1,637 km^2 (60% of cropland area) with ESI of <0.7 was detected at the beginning of the pre-rice niche (from 19th to 26th of July). The southern and eastern croplands showed generally drier soil conditions (i.e., higher ESI) than the northwestern croplands. In addition, the northwestern fringe areas seemed to have less soil moisture stress than all other areas. The above-highlighted pre-rice and post-rice cropping niches are possibly longer and with more reliable soil moisture availability in the north-western cropland area as well as along the south-eastern fringe of the floodplain.

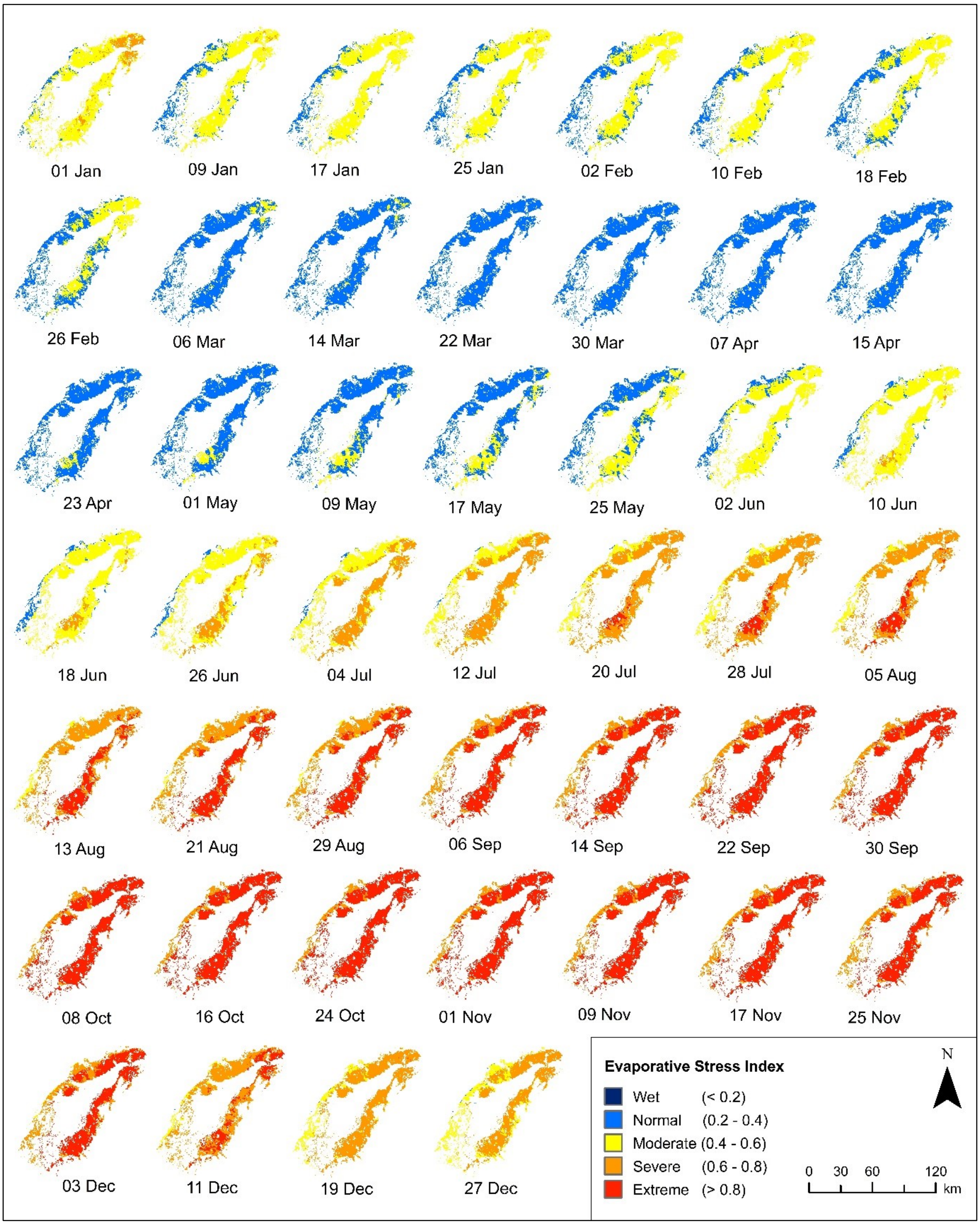

Fig. 3.4. Spatial distribution of evaporative stress index (ESI) long-term mean (2000–2019) at 8-day time steps across the cropland area of Kilombero floodplain in Tanzania.

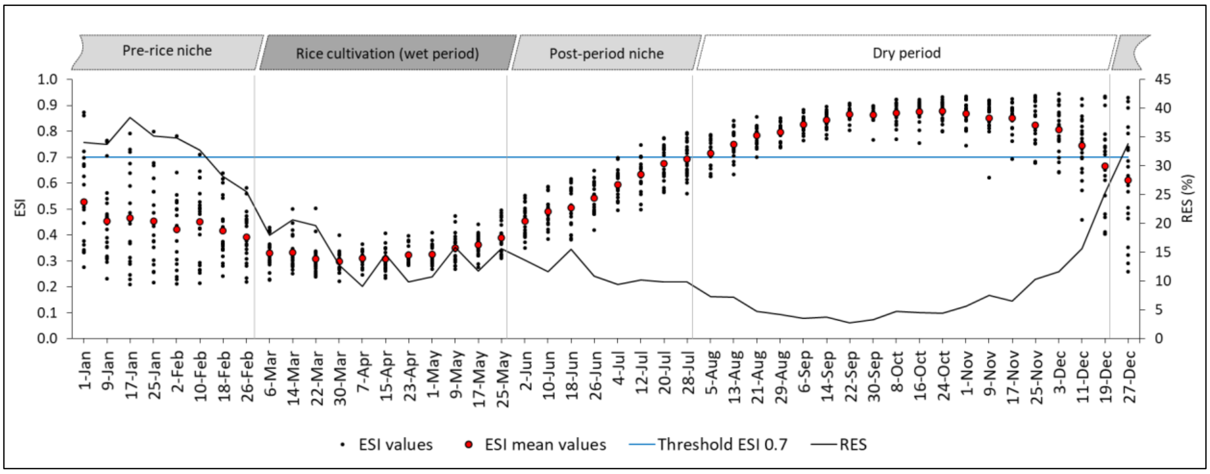

Fig. 3.5. Temporal distribution of the evaporative stress index (ESI) and the relative evaporative stress (RES) at 8-day time steps from 2009 to 2020 across the cropland area of Kilombero floodplain in Tanzania (the horizontal axis presents calendar dates at the beginning of each 8-day period which may slightly differ in leap years).

The analysis of the relative evaporative stress index (RES) provided further insights on the risks and opportunities of cultivating the pre- and post-rice niches (Fig. 3.5 and 3.6). The rainy season (March–May) exhibited RES values between 9% and 20%, in addition to the lowest ESI long-term mean values. The RES values indicated high inter-annual variability (>30%) over the period from late-December to mid-February, implying the high risks associated with cultivating during this period. While RES showed high stability (3%< RES <15%) between June to mid-December, this represents the dry period and hence a stability of low soil moisture or drought with ESI values >0.7. While pre-rice cultivation is associated with high variability and consequently with a high risk of drought-induced crop failure for farmers, post-rice cultivation (recession cropping, with or without supplemental irrigation) appears promising for dry season cultivation with moderate soil moisture availability and little risk of drought-related crop failure (9%< RES <15%).

3.3.3. Green Water Availability

The daily average (2009–2020) AET calculated from the ensemble product over the entire cropland area of Kilombero floodplain was 2.63 mm/day, corresponding to approximately 960 mm/year. These AET values were compared to the NDVI by a linear regression at multi-annual monthly basis (Fig. 3.7). Both variables correlated linearly and positively, with R^2 of 0.58 ($p < 0.05$), indicating a relatively good performance of our ensemble AET product.

The mean ensemble AET spatial and temporal distributions for each 10-day period are presented in Fig. 3.7 and 3.8. It is expected that AET values of the period March to May would be higher than the rest of the year, with a noticeable decline in June that is the harvesting month. This observed AET variability could be attributed to vegetation growth patterns as explained by the estimated NDVI; during the rice growing season, the roots enable higher AET rates through moisture access of deeper soil profile layers, while in very sparse vegetation or bare soil conditions, those deeper soil layers are disconnected from the evaporation fluxes and AET only occurs from the topsoil layer (Fig. 3.7).

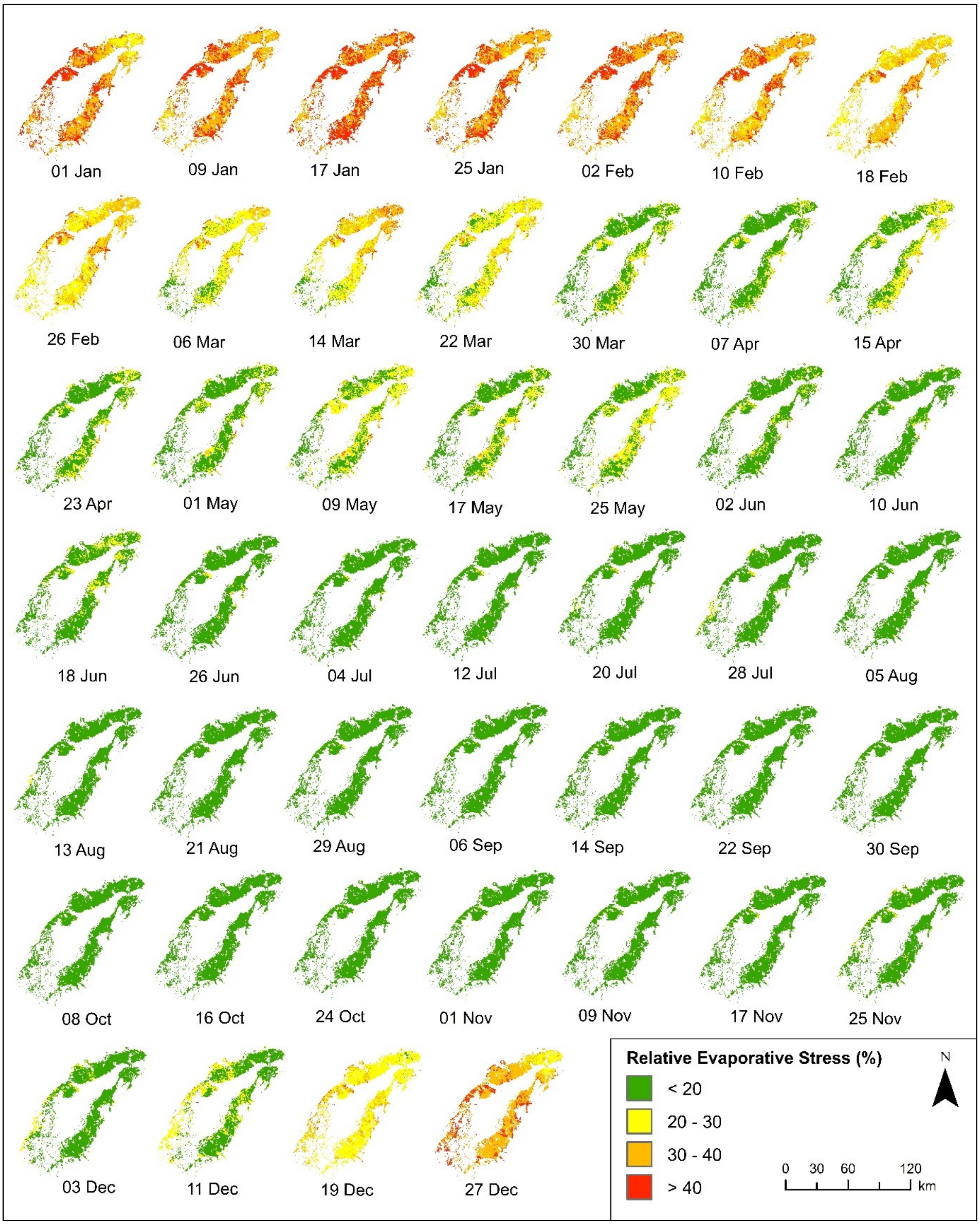

Fig. 3.6. Spatial distribution of the relative evaporative stress (RES) long-term mean (2000–2019) at 8-day time steps across the cropland area of Kilombero floodplain in Tanzania.

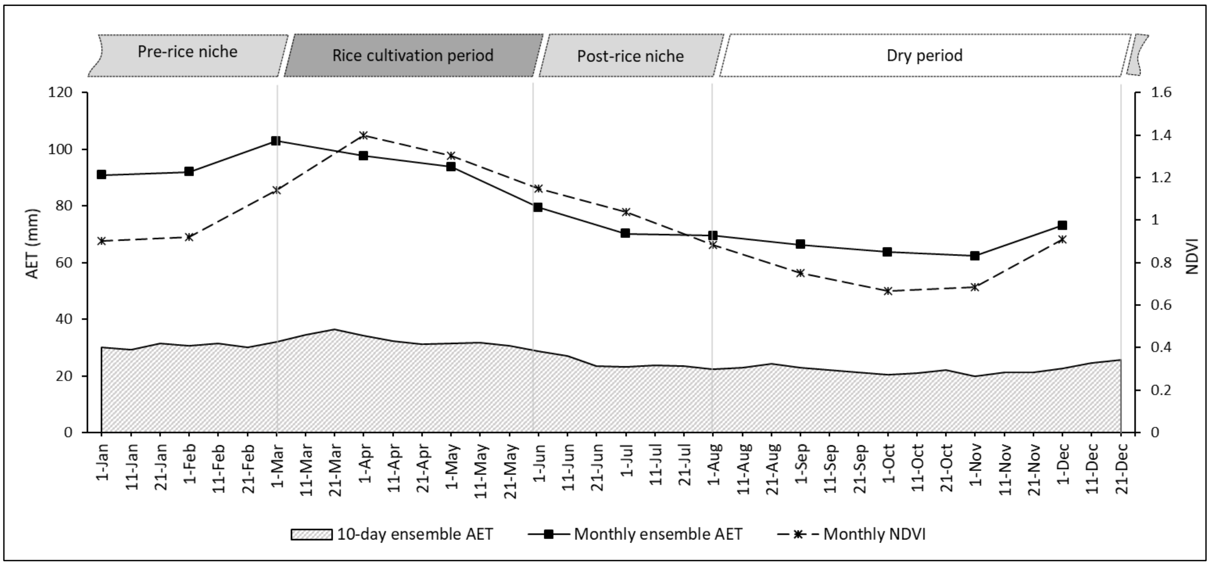

Fig. 3.7. The temporal analysis of green water availability as estimated by the actual evapotranspiration (AET) ensemble mean product 10-day and monthly time steps for the cropland area in Kilombero floodplain. Grey shading represents the multiannual average AET values for each 10-day period of the year (2009–2020). The solid and dashed lines represent the monthly comparison between AET and the normalized difference vegetation index (NDVI) from 2009 to 2020.

The AET spatial distribution revealed no substantial variability over Kilombero cropland for each 10-day period, with dominating AET values of 10–40 mm/10-day throughout (Fig. 3.8). The rainy season (March–May) showed the highest AET (mostly about 30–40 mm/10-day) of the year over Kilombero. From mid-December until late February, AET had values between 20 and 40 mm/10-day over almost all Kilombero cropland. The post-rice niche period in June and July showed that some cropland areas dry out faster, with relatively lower AET range (10–30 mm/10-day). The dry period from early August to early-December was also confirmed to have the lowest AET (<20 mm/10-day).

The aggregated AET of the pre- and post-rice niches are shown in Fig. 3.9a and 3.9b. Interestingly, the pre-rice niche (70 days) showed higher aggregated AET value ranging from 50 to 350 mm (Fig. 3.9a). Lower aggregated AET range (50–250 mm) were estimated during the post-rice niche of 60 days (Fig. 3.9b). The north-western fringes areas exhibited the highest aggregated AET values, particularly during the pre-rice niche.

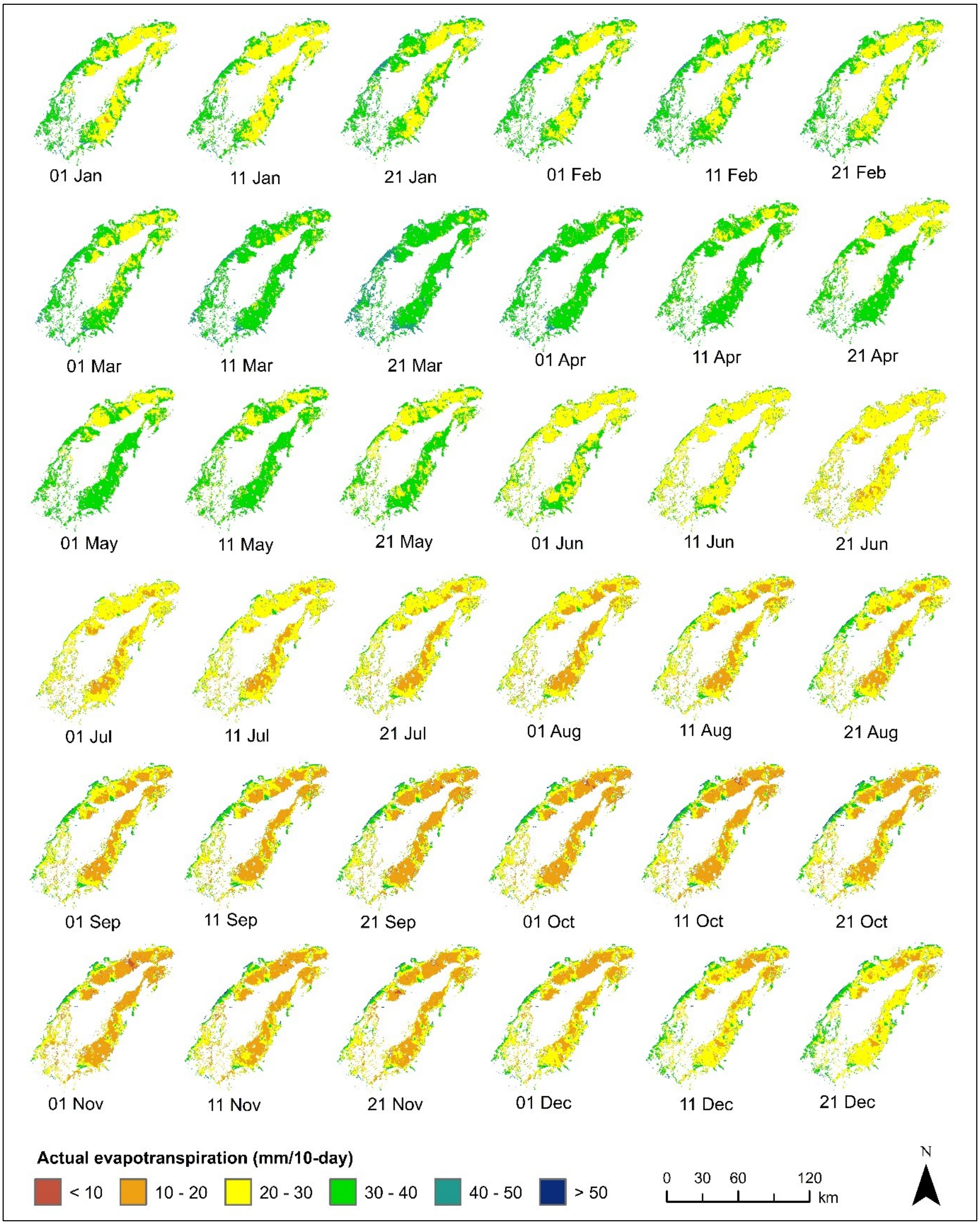

Fig. 3.8. Spatial distribution of the actual evapotranspiration (AET) ensemble mean product at 10-day time steps across the cropland area of Kilombero floodplain in Tanzania.

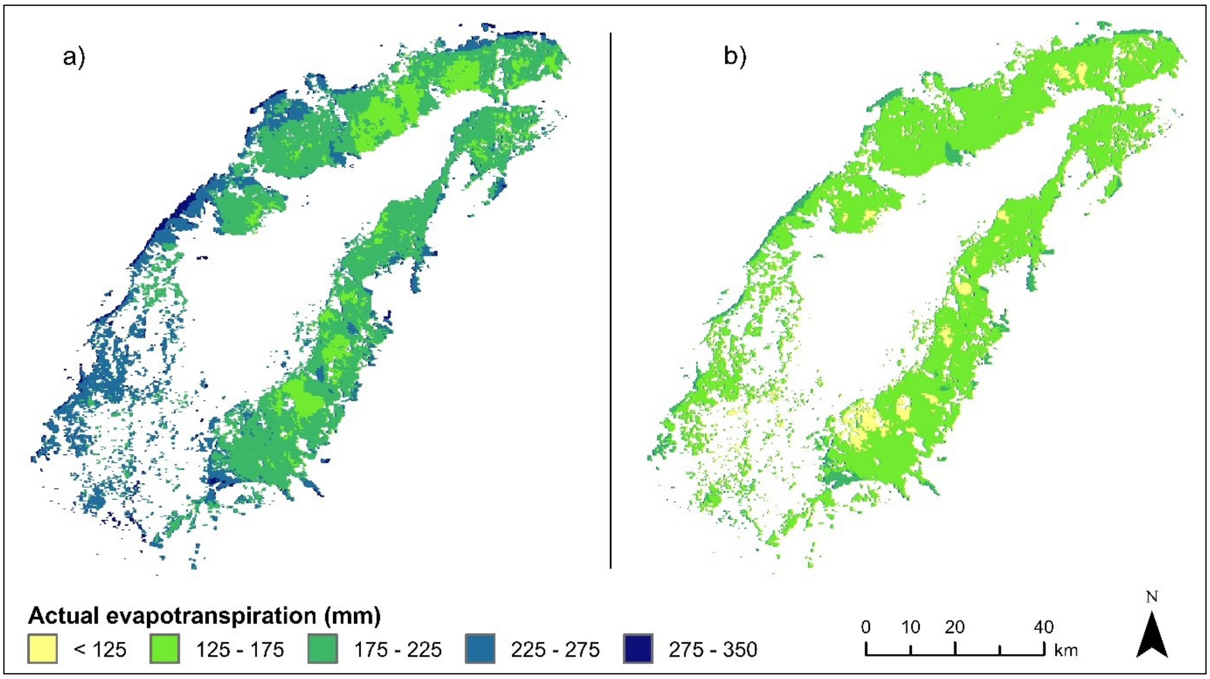

Fig. 3.9. Aggregated actual evapotranspiration (AET) values (long-term average 2009–2020) from the ensemble mean AET product in the (a) pre-rice niche (from mid-December to late February) and (b) post-rice niche (from late May to late July) across the cropland area of Kilombero floodplain in Tanzania.

3.4. Discussion

3.4.1. Suitability of using land cover and actual evapotranspiration datasets

As demonstrated in the land cover analysis (Section 3.3.1), significant disparities were found among the different land cover products. The errors can be as large as to miss-capturing or even not capturing at all a specific land cover class. Using land cover products without evaluation can lead to drawing irrelevant and misleading conclusions regarding the study area and land cover class in question. Thus, we emphasize the importance of evaluating a few land cover products for each individual case study, and subsequently choosing one. It is recommended to conduct cross-comparisons between selected products and/or to compare them against independent reference datasets, as previously done at the country (e.g., Ayyad and Khalifa, 2021), continental (e.g., Fritz et al., 2010), or global scales (e.g., Pérez-Hoyos et al., 2017). Evaluating land cover products is especially important when researching African croplands, where multiple factors influence prevailing spatial discrepancies, such as elevation dispersion, cloud cover, or size of fields (Nabil et al., 2020).

The cropland in Kilombero is dominated by rainfed lowland rice which is often difficult to differentiate from wet savanna grassland, and MCD12Q1 and ESA-CCI were unable to make this distinction. In addition to the spatial consistency observed between WaPOR and GFSAD and ESA-CCI-S2 (Section 3.3.1), the cropland area identified by WaPOR in 2015 (2,730 km^2)

also compared well with previously-reported areas of Kilombero cropland of about 2,760 km^2 in 2009 (Munishi and Jewitt, 2019), 3,000 km^2 in 2014 (Thonfeld et al., 2020a), and 3,253 (± 679) km^2 in 2014 (Thonfeld et al., 2020b). Differences between these estimates and WaPOR are attributed to a portion of the cropland falling within the seasonally inundated area close to the river. This temporarily submerged area of about 1,100 km^2 (Thonfeld et al., 2020a) consists actually of a savanna grassland grazed by ruminants during the dry season.

At the same time, AET products should be used carefully. In this study, not only did our ensemble AET product correlate well with NDVI (Section 3.3.3), but also the calculated average AET value of 2.63 mm/day (~ 960 mm/year) compared very well with AET values reported in relevant studies. For example, the average AET value in the cropland areas from the ensemble product was 2.63 mm/day (~ 960 mm/year). Weerasinghe et al. (2020) estimated an AET value of 750–1000 mm/year (~ 2.05–2.74 mm/day) following the water balance closure in the Rufiji Basin. Näschen et al. (2018) simulated hydrological fluxes in the Kilombero Basin and reported a similar AET range of 750–950 mm/year (~ 2.05–2.60 mm/day) in the sub-basins covering the area of Kilombero cropland. Similarly, Gabiri et al. (2018) calculated the soil water fluxes in Kilombero and reported an average annual AET value of 970 mm/year (~ 2.65 mm/day). In contrast, Senkondo et al. (2019) estimated the daily average AET values over different land cover types using an ensemble mean derived from three AET models. They found that the average daily AET over Kilombero cropland was 3.5 mm/day, and that SSEBop underestimated the AET values. The difference between our estimates and theirs may be attributed to two factors: (i) they used the ESA-CCI land cover product which we earlier demonstrated its inaccuracy in capturing the extent of cropland in Kilombero (Section 3.3.1), and (ii) their ensemble mean is constructed based on the surface energy balance concept solely, while our ensemble blends the SSEBop and ETLook concepts (Section 3.2.6).

3.4.2. Soil moisture conditions and green water availability

Attention should be paid to the ESI original classification (Section 3.2.5). Yao et al. (2010) highlighted the need to explore the application of the original classification in different ecosystems. While the original classification considers ESI of >0.6 to represent severe drought conditions, in this study we used 0.7 as a threshold above which crop growth may be hampered. ESI values of <0.2 represent wet conditions according to the original classification. In the case of Kilombero, the wettest ESI conditions were found to be in the range of 0.2–0.4 (Fig. 3.4 and 3.5), a range that represents “normal” drought conditions (not negatively affecting crop performance) based on the original ESI classification. Thus, we suggest that ESI classification should be adapted to the specific case study. Similarly, while we categorized

RES values into four classes (RES <20%, 20%< RES <30%, 30%< RES <40%, and RES >40%) (Section 3.2.5), future studies may opt to categorize RES differently according to the local conditions of the case study in question.

The spatial and temporal distributions of ESI and AET showed agreements with findings of previous relevant studies in the region. For instance, the spatial distribution of our ESI and AET ensemble product was consistent with findings of Burghof et al. (2018) and Gabiri et al. (2018), indicating the wetter conditions (higher AET values and lower ESI) during most of the year in the northern and western fringes than all other areas in Kilombero floodplain (Fig. 3.4 and Fig. 3.8). Gabiri et al. (2018) attributed the wetter conditions at the fringes zones to the soil water storage and the low depth to groundwater level throughout the year. In the remaining areas, and due to the land cover changes in the basin, a decrease in low flows and an increase in high flows affected the hydrological regime of the Kilombero river, i.e., inundation height and duration during the rainy season and surface-groundwater interaction during the dry season, and thus altering the soil water availability in the floodplain (Leemhuis et al., 2017).

The analyses of AET suggest that more green water is available in the pre-rice niche than the post-rice niche (Section 3.3.3). Nevertheless, the latter niche was found to be more stable over time (low RES) which offers substantial opportunities for developing green water cultivation during this niche (through recession cropping and with or without supplemental irrigation). At the same time, the pre-rice niches showed higher variability in water availability and evaporative atmospheric demands (higher RES), and thus cultivating during this period entails risk of drought or crop failure to the farmer (Section 3.3.2). Here, it seems reasonable to establish supplemental irrigation practices in the pre-rice niches to cope with dry spells, using existing irrigation canals (Alavaisha et al., 2021) and rivers stemming from adjacent mountains (Wilson et al., 2017) in some areas of Kilombero.

Our findings assessed and demonstrated green water availability before and after the wet season in Kilombero. The analyses of the absolute and relative green water availability provided useful insights as to when, where, and how reliable is green water availability beyond the wet season in view of maximizing the potential of agricultural production on existing cropland and with minimal impact on natural processes. This can be done by shifting a portion of the nonproductive green water flows (i.e., soil evaporation) to productive vapor flows in form of crop transpiration (Rockström, 2003). Thus, other water fluxes, i.e., runoff and seepage, shall not be significantly affected. Shifting AET fluxes to productive vapor flows will not only preserve natural processes and halt cropland expansion but will also contribute to improve the livelihoods, food security, and resilience of smallholder farming communities.

Two important points should be considered when planning to shift the AET fluxes to productive crop transpiration. First, the estimated AET herein is the sum of soil evaporation, plant transpiration, and evaporation of intercepted rainwater. Transpiration, the productive plants' water consumption, ranges from 66% to 92% of the total AET estimated over cropland globally (Miralles et al., 2011; Wang-Erlandsson et al., 2014; Wei et al., 2017). This is especially important when designing cultivation strategies in the pre-rice niche, where interception of early-season rainfall events will occur and thus not all the estimated AET in this niche will be available for the plants. Second, it should be noted that in the pre- and post-rice niches with very sparse vegetation, the estimated AET values only represent green water fluxes that occur primarily from the 2–5 cm topsoil layer (Anderson et al., 2007). However, more green water is likely to be available at deeper layers of the soil profile and, thus, the cropping niches could potentially be even longer. For instance, while we estimated a post-rice niche of 65 days, Kangalawe and Liwenga (2005) conducted participatory assessments and reported that the post-rice soil moisture period in some areas in Kilombero may last for three to six months. On the other hand, they further highlighted that some areas dry out shortly after the rains have ceased, depending on the soil texture and the water-holding capacity. Therefore, differences in green water availability (Fig. 3.8) can also be attributed to soil hydraulic properties, e.g., soil texture, organic matter, saturated and residual water content, water-holding capacity, and hydrologic soil group.

3.4.3. Prospect of sustainable intensification and diversification

From an agronomic perspective, several cropping options can well fit within the pre- and post-rice niches. One the one hand, rice double cropping may be possible in some areas where the availability of green water extends longer into the post-rice niche. Moreover, extended water availability may permit to growing long-duration rice cultivars, which are frequently economically and socially preferred (Changalima et al., 2020). Diversification options, on the other hand, may include a broad set of possibilities. For instance, some farmers in Kilombero produce maize, vegetables, cassava, cowpeas, and pigeon peas (Gebrekidan et al., 2020; Höllermann et al., 2021), and these crops can fit well within the detected niches. Also, short-cycled green manure crops can produce biofertilizer in the pre-rice niche, while deep-rooted forage legumes such as Stylosanthes can extract water from deeper soil layers, thus extending the length of the post-rice niche for producing forage for cattle feeding (Kwesiga et al., 2020b). Moreover, perishable vegetable crops, particularly leafy vegetables, can be grown for as long as water is available (Verhoeven and Setter, 2010).

Important considerations entail also the inter-annual changes in soil moisture conditions across the cropland in the floodplain. In the pre-rice niche (after a prolonged dry season), the soil condition gradually changes from hard and dry to soft and wet, triggered by the onset of rainfall events. Conversely, the soil gradually moves from the wet and soft conditions back to the hard and dry conditions during the post-rice niche after the seasonal inundation recedes (towards the dry season). These changes in the soil moisture conditions will partly govern the selection of pre- and post- rice crops. For example, the shift from hard-dry to soft-wet conditions in the pre-rice niche may offer an opportunity to cultivate, e.g., tuber crops such as cassava, sweet potatoes, and carrots, which cannot be cultivated in the post-rice niche because of the hard-dry soil conditions by the harvest time. However, tuber crops in the pre-rice niche will not be able to tolerate submergence conditions. Thus, to avoid crop submergence and to increase the rooting depth, building ridges for crop cultivation may be required in both niches, implying hard physical labor or the use of machinery, which can be economically challenging for low-input farmers with limited resource endowment. The changes in the soil aeration and physical status entail not only niche-specific hydrologic dynamics but may also entail different dynamics in soil nitrogen availability, with compact dry soils limiting root nutrient uptake in the later post-rice niche, and nitrate accumulation and subsequent leaching and denitrification losses limiting crop nitrogen availability during the pre-rice niche (Yameogo et al., 2021).

Although farmers follow specific planting dates for rainfed rice cultivation in Kilombero, they adjust their cropping calendars and the planting dates according to (i) the water level as it rises in the floodplain and (ii) the observed weather patterns (e.g., direction of cloud formation and sound of thunder), which may vary across the floodplain (Höllermann et al., 2021). Rice is usually planted between late February and early March but the planting date can vary across Kilombero by a few days, and between years by a few weeks depending on the onset of the rainy season (Kwesiga et al., 2019). Thus, the planting time of the rainfed rice can shorten or prolong both the pre- and post-rice niches and thereby influence the choice of diversification crops in both niches and across the floodplain.

Another critical determinant to crop selection is the proximity and availability of markets in the region. Perishable crops with a short storage life, such as tubers crops (e.g., carrots) or other leafy vegetables (e.g., cabbages), need to be delivered to the market as soon as they have been harvested, restricting this option to peri-urban areas, such as Ifakara town in Kilombero (Fig. 3.1). Coarse grains such as rice, maize, or sorghum have longer storage lives and may be thus preferred in remote or rural areas.

3.4.4. Broader implications of green water cultivation for Africa and beyond

Green water contributes about 87% of the global cropland water consumption (Liu and Yang, 2010) and substantial opportunities exist towards building more productive agricultural rainfed systems, relying on green water, which can ultimately reduce the pressure on blue water resources (Wani et al., 2009). In Africa, over 90% of cropland is rainfed (Xiong et al., 2017a) and depends on green water (Liu and Yang, 2010) that is much more available than blue water (Schuol et al., 2008). Yet, only 5% of public agricultural water investments support rainfed agriculture in Africa (Abrams, 2018). Our analyses of green water availability can guide investments in floodplain wetlands of SSA. The detected patterns of water availability are crucial to inform farmers, decision-makers as well as international and national donors/investors areas as to where and when investments will likely yield higher returns. This is not only important for improving rainfed cultivation practices through improved field management techniques, e.g., rainwater harvesting technologies (Biazin et al., 2012) or native soil N management (Asante et al., 2017), but also for considering irrigation investments where green water availability, solely, does not permit for crop cultivation. Here, investing in supplemental irrigation will contribute to increasing the overall agricultural production and resilience to dry spells (Rockström et al., 2010).

As mentioned earlier, wetlands, and especially the seasonal floodplain wetlands, contribute significantly to livelihood and food security in SSA (Rebelo et al., 2010). Therefore, creating more sustainable intensification and diversification options in floodplain environments, such as efficiently exploiting available green water availability, can significantly contribute to improving food security and livelihoods by realizing the agricultural potential while halting the cropland expansion, an expansion that is not needed to meet both today’s and future biomass demands (Mauser et al., 2015). Although applied to rather local scales of floodplain environments, implementing and upscaling such green water management strategies can play a pivotal role towards a much-needed shift in the African water management (Falkenmark, 2018). On a broader scale, these strategies can ultimately contribute to keeping agriculture within the safe operating space of the planet boundaries (Rockström et al., 2017) while realizing multiple SGDs simultaneously.

3.4.5. Limitations and future research

Remote sensing datasets with extensive spatial and temporal coverage provide large opportunities for a wide range of agricultural studies (Jindo et al., 2021), however, challenges may prevail due to entailed uncertainties of using such datasets (Karimi and Bastiaanssen, 2015). Validation of these datasets is thus imperative yet challenging, and sometimes is unfeasible due to the scarcity of ground data and the mismatches between gridded and ground datasets. For instance, to validate remotely-sensed AET estimates, they can be compared against *in-situ* measurements from eddy covariance towers, lysimeter systems, or by the water balance closure (Allen et al., 2011). Such measurements were not obtainable in Kilombero. Creating an ensemble mean of reported AET products with good performance and already documented uncertainties can thus provide a reasonable alternative. Further, despite uncertainties associated with the MOD16A2GF products for AET and PET (Running et al., 2019), our calculations relied on their relative rather than absolute values for calculating ESI and RES to identify the pre- and post-rice niches (Section 3.2.5). Nonetheless, future research should validate the spatial and temporal boundaries and the quantified AET of the identified niches. Although the chosen products in this study were carefully selected, evaluated, and demonstrated good performance, we recommend using locally-produced/calibrated datasets whenever possible, when applying the proposed methodological approach in future research.

The scale of the study should also be considered when choosing specific remote sensing products. This study looked at the full extent of cropland areas and thus the selected products were considered to have sufficient spatial resolution (100–500 m). When looking at smaller scales (e.g., field or plot level), AET and cropland maps of higher resolutions (10–30 m) can be derived from satellite images with higher resolutions (e.g., Landsat and Sentinel). There is also a critical need for operational and temporally dynamic land cover products to better understand the intra-annual changes in cropland areas of seasonal floodplain wetlands.

Although it was beyond the scope of this study, an agronomic analysis that classifies crop functional traits and determines their fit within specific cropping niches is needed to target and extrapolate sustainable crop intensification and diversification strategies. Future research can further refine our results by investigating soil properties through field studies to assess soil suitability and to understand why some cropland areas dry out faster in the post-rice niche. In the light of reported findings herein, further field experiments combined with stakeholder analysis and aspiration mapping (e.g., Höllermann et al., 2021) are needed to identify and spatially target future site- and system-specific land use strategies for sustainable diversification and intensification of seasonal floodplain wetlands. To ensure the transferability of the findings of this research, the approach proposed in this study needs to be tested and validated in other seasonal floodplain wetlands in SSA. Thus, it is imperative to detect and analyze seasonal floodplain wetlands in SSA with similarities to Kilombero to which the suggested approach could be extrapolated and niche-specific targeting of crop diversification be applied.

3.5. Conclusions

Using Kilombero as a case study, we could show that seasonal floodplain environments exhibit substantial potential for future sustainable crop intensification and diversification in sub-Saharan Africa. Farmers cultivating floodplains use submergence water to grow rice during the wet season. Before and after the wet season, farming activities are limited, mainly due to water (un)availability and variability. We proposed a methodological approach that relies on open-access remote sensing datasets and permits to identify where, when, and how much green water is likely to be available beyond the rice cropping season.

Land cover products showed huge disparities in extracting cropland areas with WaPOR being the best-performing product to delineate areas under rainfed rice production in Kilombero. Furthermore, creating an ensemble mean of reportedly well-performing actual evapotranspiration (AET) products seems to be a viable option for data-scarce regions such as Kilombero. Herein, the ensemble mean product of WaPOR and SSEBop demonstrated good quality for estimating AET in Kilombero.

Green water is available both before and after the rice cropping season. The analyses of the ensemble mean AET product suggests that more green water is available in the pre-rice than the post-rice niches and that distinct spatial patterns of water availability are apparent. Both the evaporative stress index and the newly-proposed relative evaporative stress index appear to be suitable indicators to analyze and map soil moisture conditions in these so far unexploited cropping niches.

Sustainable cultivation practices using green water in seasonal floodplain wetlands provide tremendous opportunities to intensify agricultural production and consequently improving farmer livelihoods, not only in Kilombero but also in other seasonal floodplains of sub-Saharan Africa and beyond.

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4. The Nile Delta in Egypt

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Abstract

Similar to numerous water- and data-scarce regions, Egypt confronts a critical challenge in sustaining food production for its rapidly growing population. Consequently, the country’s water and land resources are under considerable stress and require careful management. About half of Egypt's both annually harvested areas and renewable freshwater are allocated for cultivating rice, maize, wheat, and berseem clover. However, the extent to which crop production might be improved and how this would impact future water and land requirements remains poorly understood. We analyzed potential improvements in the production of these crops and quantified their future water and land requirements under different scenarios. Potential improvements were detected through percentile analysis in three remote sensing-derived performance indicators for each crop in the Nile Delta’s Zankalon region: (i) crop yield, (ii) crop water productivity, and (iii) transpiration fraction (transpiration to actual evapotranspiration, T/AET). We applied detected improvements to construct plausible scenarios for Egypt’s water and land requirements to sustain domestic crop production until 2050.

Our findings indicate limited potential to improve T/AET (<4%). However, improvements of up to 27% for crop yields and up to 14% for water productivity are possible. To meet the production targets by 2050, national production must increase by 128, 78, 69, and 71% above the 2016–2020’s average for rice, maize, wheat, and berseem, respectively. Depending on the improvement levels in the developed scenarios, a total harvested land area between 5.3 and 6.4 million ha will be required by 2050, with 18% allocated to rice, 28% to maize, 36% to wheat, and 18% to berseem. Associated freshwater requirements will amount to 59–68 billion cubic meters, divided into 23% for rice, 34% for maize, 28% for wheat, and 15% for berseem. Interventions increasing yields and water productivity will benefit more the summer (rice and maize) than the winter crops (wheat and berseem). We discuss likely interventions for meeting these requirements and for sustaining the supply of these crops in Egypt.

4.1. Introduction

Water scarcity and the inefficient use of water resources for food production are critical and persistent challenges in various developing regions around the world. These challenges are especially noticeable in the arid and hyper-arid zones of North Africa, where the dual impact of climate change and rapid population growth is expected to further exacerbate existing water scarcity issues (Schilling et al., 2020). Egypt, the most populous country in North Africa (Worldometer, 2023), faces significant challenges related to its water resources and food production due to its unique geographical and hydrological circumstances. The Nile River is the primary source of blue water in Egypt (water in rivers, lakes, and aquifers). Egypt receives about 55.5 billion cubic meters (BCM) from the Nile and 1.0 BCM from the Nubian aquifer (AQUASTAT, 2016). About 2.0 BCM of freshwater originates from internal effective rainfall, resulting in a 97% dependency on external water resources (Ayyad and Khalifa, 2021). Egypt's supply of available blue freshwater is projected to decline from 570 to 360 cubic meters per capita by 2050, implying a state of absolute water scarcity (Ayyad and Khalifa, 2021).

While the total renewable freshwater resources stand at 58.5 BCM, total water abstractions amount to 80 BCM (Omar and Moussa, 2016). This gap is mainly mitigated through extensive water reuse and non-renewable groundwater extraction. However, the reuse of drainage and sewage water in the Nile Delta affects negatively its soils, crop productivity, and human health (Kheir et al., 2021a), while the heavy reliance on fossil groundwater leads to its depletion and salinization (El-Agha et al., 2023). Agriculture is the largest consumer of water in Egypt, receiving about 62 BCM for the predominant surface irrigation practices to mainly produce food (AbuZeid, 2020). Additionally, Egypt imports about 50 BCM and exports 7.0 BCM of virtual water embedded in food crops annually, making the country a net importer of at least 40 BCM of virtual water (Abdelkader et al., 2018; AbuZeid, 2020; Nikiel and Eltahir, 2021). Therefore, further blue water scarcity can induce shortages in food supply, surges in food prices, and food insecurity, thereby increasing the vulnerability of the agricultural sector and communities.

With a limited scope for further developing water resources, Egypt is likely to face serious challenges in securing sufficient additional water to boost food production to keep pace with its rapidly growing population and will likely continue relying on food imports especially for cereals (Abdelkader et al., 2018; Ayyad and Khalifa, 2021; Nikiel and Eltahir, 2021). To sustain crop production by 2050 under current production efficiencies, Egypt would need 110 BCM of water instead of the 62 BCM currently allocated for agriculture, which may not be feasible given the country's limited water budget (Ayyad and Khalifa, 2021). This projected rise also highlights the need for expanding the cultivated area. Despite a cropping intensity of 190% (at least two crops per year on >90% of the cropland area - CAPMAS 2023), Egypt will still need to expand its currently harvested area of 6.6 million ha (Mha) to 9.2 Mha by 2050 (Ayyad and Khalifa, 2021). These projections reveal the significant hurdles Egypt will encounter in securing water and land resources for future crop production, without accounting for future food imports, industrial and domestic water usage, and the anticipated impacts of climate change that are expected to increase crop water requirements (Mostafa et al., 2021).

Given their strategic significance for Egypt, food crops with strategic significance, such as rice (*Oryza sativa*), maize (*Zea mays*), and wheat (*Triticum aestivum*), and the forage crop berseem clover (*Trifolium alexandrinum*), dominate the cultivated cropland area and contribute the major share of daily calories for its population (FAOSTAT, 2023). At national scale, rice, maize, wheat, and berseem occupied an average of 7, 15, 20, and 10% of the total harvested areas in Egypt during the period from 2016 to 2020, respectively. During the same period, Egypt allocated about 8.5, 9.0, 6.5, and 4.0 BCM per year of irrigation water for cultivating rice, maize, wheat, and berseem, respectively, accounting for almost half of Egypt's total renewable freshwater resources (CAPMAS, 2023). Additionally, Egypt is currently a net importer of wheat, maize, and rice given the gap between the country's domestic production capacity and demand for these crops (FAOSTAT, 2023). Nevertheless, the extent to which the production of these crops might be improved and how this would impact future water and land requirements remains poorly understood.

Several studies estimated the water and land resources required to sustain future crop supply in Egypt (e.g., Asseng et al. 2018; Abdelkader et al. 2018; Abdelaal and Thilmany 2019; Ayyad and Khalifa 2021; Nikiel and Eltahir 2021). While these studies adopted scenario-based approaches and used various methods and datasets, they lacked a comprehensive quantification of potential improvements in crop production, specifically by enhancing water savings and increasing crop yields. Presently, there are no published studies providing in-depth information on improvements of crop yields and water savings for the main crops in Egypt. Multsch et al. (2017) assumed normative values for potential improvements in irrigation efficiency in Egypt, ranging between 5–15%. Ayyad and Khalifa (2021) estimated a potential increase in the yield of cereal crops of 10–15% and in agricultural water savings of 5–10%, using historical yield values and remote sensing data, and covering the total cropland of the country without distinguishing between specific crop types.

Against this background, it becomes imperative to understand and quantify potential improvements in the production of major crops to determine which crops and parameters require interventions. This can serve as pivotal entry points for designing interventions and guiding investments to enhance crop production and conserving vital water and land resources. Such knowledge is lacking in Egypt, and in many other developing regions, mainly due to the lack of detailed crop type maps and sufficient ground data. To explore desirable future agricultural development pathways, assessments are required that are based on integrating publicly available data and that incorporate crop-specific spatial and temporal dimensions. Our work focused on Egypt, however, there are many other developing nations with similar conditions to those of Egypt. The typical main similarities encompass (i) the significant gaps between resource availability and demand/consumption; (ii) the heavy reliance on blue water for irrigation practices; and (iii) the scarcity of ground data. Under these conditions, a comprehensive quantification of potential improvements in water savings and crop yields becomes indispensable. Moreover, exploring future water and land requirements for crop production in such regions is crucial for policymakers in order to be prepared and apply appropriate interventions in a timely manner. The quantification of potential improvements is necessary to construct plausible scenarios of future demand for resources. Not only does the spatio-temporal analysis of crop yields and water consumption help quantify potential improvements that are used to construct future scenarios, but it also allows to highlight opportunities in improving specific crop parameters and to set priorities when applying interventions.

In this study, we quantify the potential improvements in three remote sensing-derived performance indicators for rice, wheat, maize, and berseem in a benchmark case study in the Nile Delta (the Zankalon region). These indicators comprise (i) crop yield: the harvested production per unit of land area, (ii) crop water productivity (CWP): the harvested production per unit of water consumed (actual evapotranspiration, AET), and (iii) transpiration fraction (T/AET): crop transpiration to actual evapotranspiration. Based on this quantification, we extrapolate the detected potential improvements from Zankalon to the national level of Egypt and construct plausible scenarios of future water and land requirements to sustain domestic production of the four crops until 2050. Subsequently, we propose a set of interventions to address the future challenge of sustaining the supply of these crops in Egypt. The novelty of our study lies in (1) the detailed quantification of potential improvements at the crop level, (2) providing outlooks as to how these improvements will influence the future demand for water and land in Egypt, and (3) the developed methodological approach, integrating multiple types of open-access datasets to quantify improvements in crop production and project demand for crops and resources in data-scarce regions. Such insights will permit to pinpoint opportunities to enhance production efficiency and to conserve water and land resources in the future. Our findings and the methodological approach are useful for and potentially applicable to other parts of the world, especially those with conditions similar to those encountered in Egypt, where the use of water and land resources must be improved.

4.2. Materials and methods

4.2.1. The Zankalon region of the Nile Delta

To detect potential improvements in cultivating the four major crops in Egypt, we needed to follow a crop-specific approach. In the absence of detailed crop type maps covering the entire cropland extent in Egypt, conducting such crop-specific analysis at the national level was not feasible. Therefore, we identified the Zankalon region, located mostly within the governorate of Sharkia in the Nile Delta (Fig. 4.1a), as a benchmark case study to detect the potential improvements in performance indicators for the four crops and subsequently extrapolate the findings to the national level. The choice of Zankalon was made for several reasons: (1) the extensive availability of satellite observations for crop type mapping and for estimating performance indicators at high spatial and temporal resolutions over Zankalon (Section 4.2.3); (2) Zankalon represents about 5% of the old lands under the predominant surface irrigation practices in the Nile Delta, where about 65% of all cropland in Egypt is located (Ayyad et al., 2019; Hereher, 2013); and (3) the extensive cultivation of the four crops under investigation in Zankalon and in all Egypt. During the summer season (May–October), rice and maize account for 78 and 9%, respectively, of the total cropland area in Zankalon, while 45 and 43% of the area are cultivated with wheat and berseem during the winter season (October–April), respectively (FAO, 2023b). The monthly average temperatures, precipitation, and reference evapotranspiration reflecting the seasonality in Zankalon are presented in Fig. 4.1b.

Our analysis of Zankalon aims at estimating potential improvements in performance indicators across fields in Zankalon as relative values (percentages) rather than absolute values to accommodate the understanding that absolute values from Zankalon may not be fully representative to all irrigated areas across Egypt. For these reasons, Zankalon appears to be a suitable and representative case study to detect variation in performance indicators for the four crops.

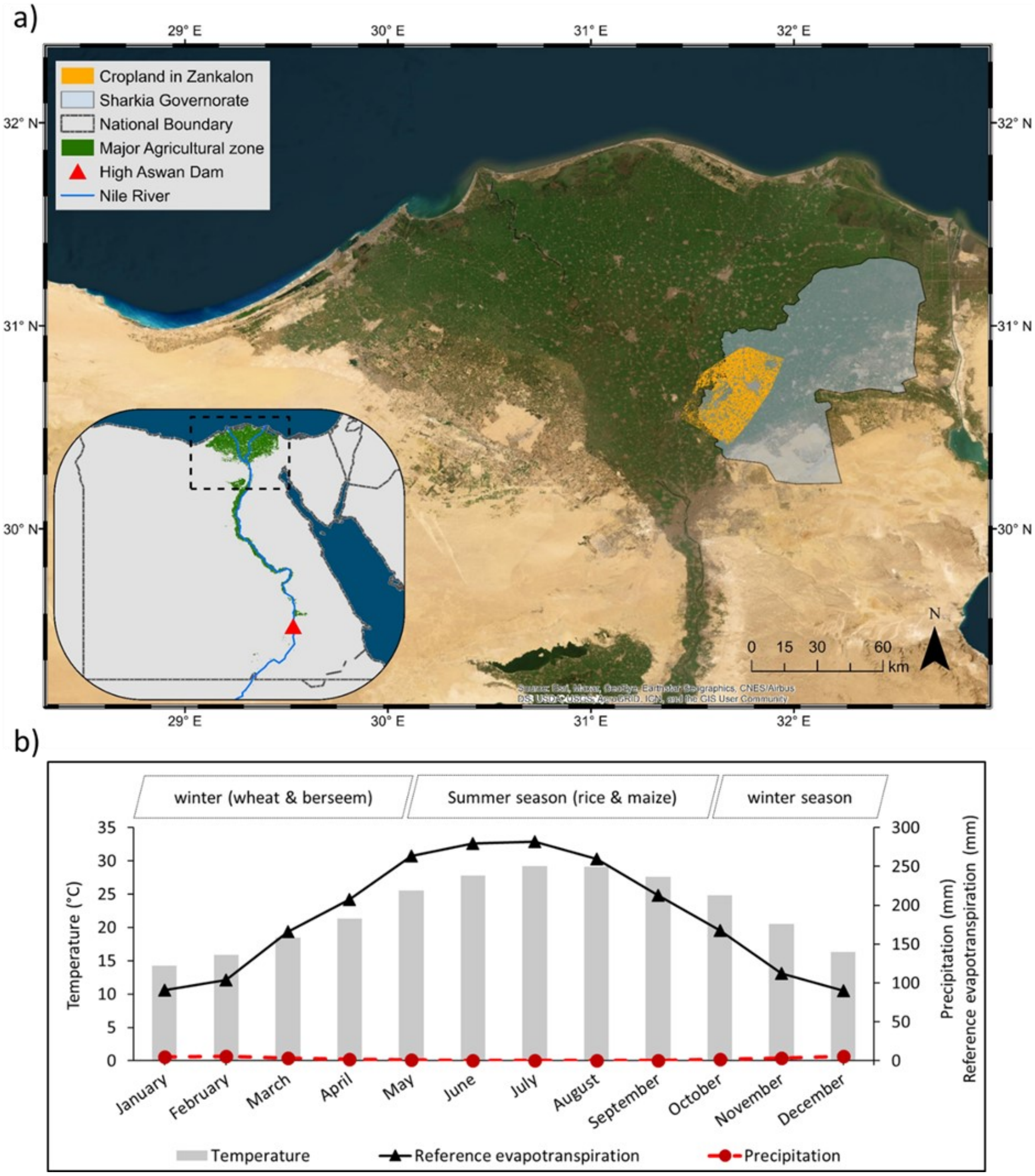

Fig. 4.1. a) Location map of the Zankalon region in the Nile Delta. Cropland areas: (FAO, 2023b), national boundary: https://www.naturalearthdata.com/, Sharkia governorate: https://www.diva-gis.org/. b) Average monthly temperatures, precipitation, and reference evapotranspiration over Zankalon for the period 2010–2019. Precipitation & reference evapotranspiration: (FAO, 2023b), temperature: (Harris et al., 2020).

4.2.2. Methodological approach

We integrated remote sensing datasets, national statistics, and secondary data from literature to quantify the potential improvements in three performance indicators in Zankalon and used this quantification to construct plausible scenarios of future water and land demands to sustain domestic production of the four strategic crops in Egypt as outlined in Fig. 4.2. The data inputs used in this study and their corresponding sources are summarized in Table 4.1. The proposed approach encompasses three phases: (i) extracting cropland areas for the selected crops and estimate their corresponding performance indicators in Zankalon, namely crop yield, crop water productivity (CWP), and transpiration fraction (T/AET) (Fig. 4.2a); (ii) benchmarking these performance indicators and estimating their potential improvements in Zankalon (Fig. 4.2b); and (iii) using the estimated potential improvements to construct scenarios of future water and land demand to sustain production of the selected crops by 2050 in all Egypt (Fig. 4.2c). We studied the most recent performance of irrigated agriculture in Egypt from 2016 to 2021.

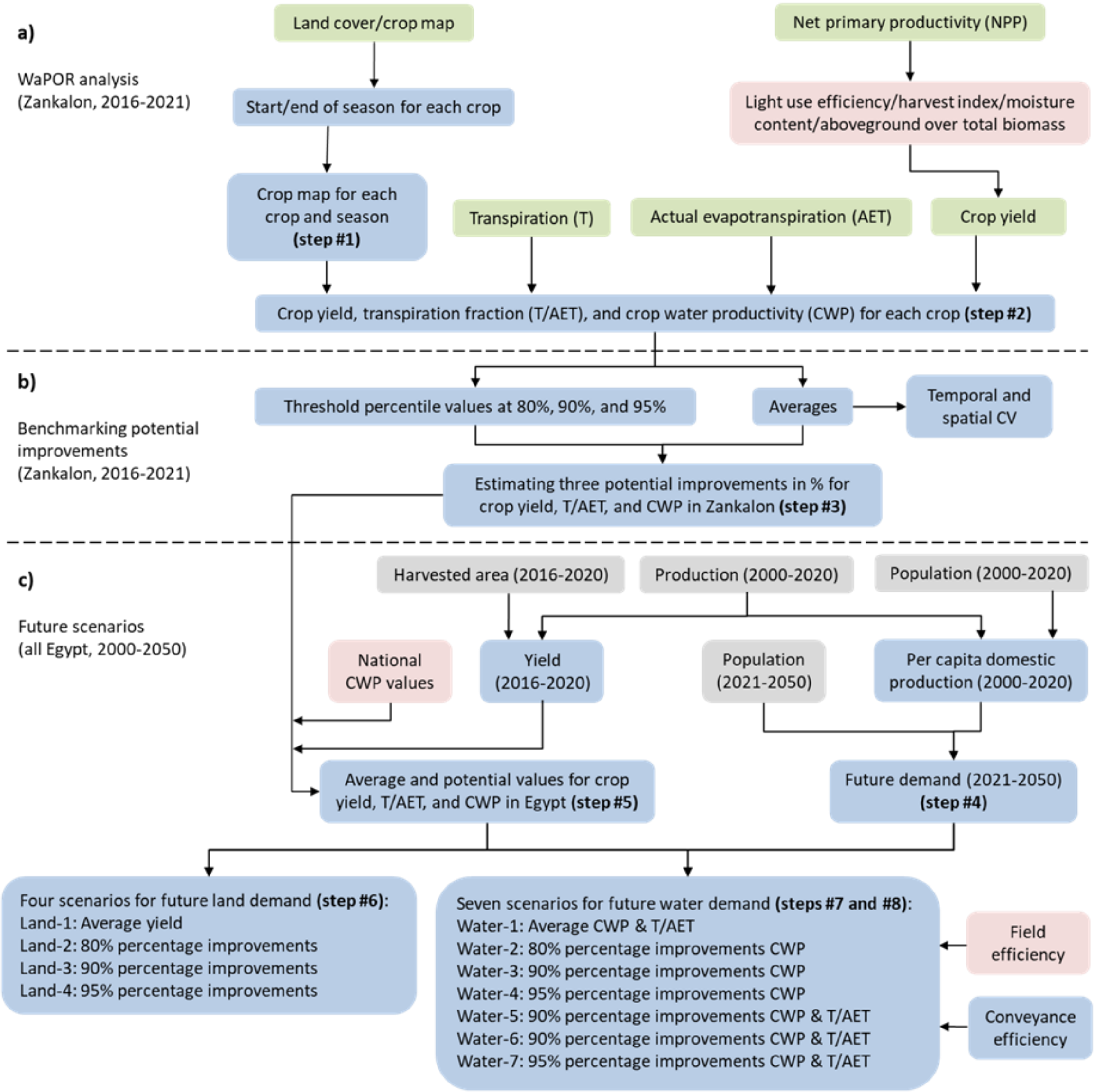

Fig. 4.2. The proposed methodological approach showing the workflow and steps. Boxes highlighted in green represent data variables distributed through WaPOR. Boxes highlighted in red are data based

on literature and those highlighted in black are sourced from secondary sources. Boxes highlighted in blue represent results of own processing.

4.2.3. WaPOR datasets

To achieve the study objectives in this data-scarce region, we used the high-resolution open-access datasets from FAO's portal to monitor water productivity through open access remotely sensed derived data (WaPOR v2.1; https://wapor.apps.fao.org/home/WAPOR_2/3) and GIS techniques. WaPOR provides datasets needed to estimate performance indicators at spatial resolutions of 250 m (level-1; covering Africa and the Near East), 100 m (level-2; for some countries and river basins), and 30 m (level-3; for some sub-national sites). Herein, we focused on the Zankalon region in Egypt covered by WaPOR's level-3 at 30 m spatial resolution and 10-day timesteps. We used multiple datasets from WaPOR to conduct this analysis (Table 4.1). WaPOR's datasets have gained recognition in recent years and have been increasingly used to monitor these parameters (Ayyad et al., 2022; Chukalla et al., 2022; Safi A. et al., 2022; Safi C. et al., 2023). The high quality of WaPOR's datasets in estimating some of these parameters is reported in literature. For example, WaPOR demonstrated high performance reproducing the conservative relationship between biomass and AET in irrigated cropland in Ethiopia and Mozambique (Seijger et al., 2023). Ayyad and Khalifa (2021) have reported the efficacy of WaPOR's land cover dataset in delineating irrigated areas within Egypt. Similarly, WaPOR performed well in estimating AET over the Nile region (McNamara et al., 2021) and was recommended for inter-plot comparison over irrigated areas in several regions in Africa (Blatchford et al., 2020). Further grounds for choosing WaPOR's data are the open accessibility through public domain, and the continuity WaPOR's mission, allowing for the operationalization and use of these products in future research. The required datasets were downloaded and processed in the ArcGIS environment (ESRI, 2019).

Table 4.1. Input data and sources used in the analysis.

Data	Type	Spatial and temporal resolution	Time period	Sources
Land cover/crop type	Satellite	30 m; 10-day	2016–2021	WaPOR
Actual evapotranspiration	Satellite	30 m; 10-day	2016–2021	WaPOR
Transpiration	Satellite	30 m; 10-day	2016–2021	WaPOR
Crop yield	Satellite	30 m; 10-day	2016–2021	WaPOR
Crop water productivity	Satellite	30 m; 10-day	2016–2021	WaPOR
Population	Time series	Annual	2000–2050	(United Nations, 2023b).
Crop statistics (rice, maize, and wheat)	Time series	Annual	2000–2020	(FAOSTAT, 2023)
Crop statistics (berseem)	Time series	Annual	2004–2020	(CAPMAS, 2023)
Conveyance efficiency	Time series	Annual	2016–2021	(CAPMAS, 2023)

4.2.4. Land cover analysis

WaPOR's level-3 land cover/crop type dataset is available at 10-day timesteps, which allows for detecting the start and end of season for each crop. We determined season lengths for each crop and season, which were then used to calculate the other variables required for the analysis. The average lengths of growing season were 150 (±5), 130 (±4), 190 (±7), and 210 (±5) days for rice, maize, wheat, and berseem, respectively. For each crop, one crop type map was extracted at the vegetative stage and used as the crop type layer for the corresponding season in further steps. The result of this step was one crop type map for each crop and season, i.e., five crop type maps for each crop for the period 2016–2021 (Fig. 4.2, step#1).

4.2.5. Performance indicators

We used three main performance indicators derived from WaPOR datasets:

(i) Transpiration fraction (T/AET, dimensionless): the ratio of transpiration (T, in m^3/ha), which pertains to the productive portion of actual evapotranspiration (AET), to the total AET (in m^3/ha) that includes both productive and nonproductive evaporation fluxes.
(ii) Crop yield (in t/ha): represents the quantity of harvest produced per unit area.
(iii) Crop water productivity (CWP, in kg/m^3): represents the yield generated per unit of water consumed and calculated as the ratio of yield to AET.

These indicators were calculated for each crop in each season and averaged over the 5-year period to alleviate potential anomalies (Fig. 4.2: step #2). Firstly, we estimated seasonal T and AET by aggregating their 10-day values of the respective growth season for each crop. Subsequently, T/AET was computed by dividing the seasonal T by the corresponding seasonal AET.

WaPOR estimates crop yield by calculating the seasonal net primary production (NPP) and converting it to aboveground biomass (AGB) (Eq. 4.1) and subsequently to crop yield (Eq. 4.2) (FAO, 2020a).

$$AGB = NPP * 22.222 * AoT \tag{4.1}$$

$$Yield = \frac{AGB*HI}{(1-\theta)} * LUE_c \tag{4.2}$$

where AoT is the ratio of aboveground biomass to total biomass. 22.222 is a scaling factor to convert NPP to dry matter (1 gC/m²/day (NPP) = 22.222 kg DM/ha/day). θ is the moisture content of the harvested biomass (in %). HI is the harvest index and represents the harvestable fraction of biomass. LUE_c refers to the light use efficiency (LUE) correction factor, representing the ratio between the actual LUE (crop-specific) and the LUE (generic value for cropland of 2.7 MJ g^{-1}) that WaPOR uses for calculating NPP (FAO, 2020b). These parameters are unique to the location and varieties under study. We compiled crop parameters from relevant literature sources for the four crops under investigation and used their averages (Table 4.2). We found values for some of these parameters specifically for crops in Egypt. For other parameters, we relied on values reported from crops in other arid and semi-arid regions such as Australia, India, China, and the USA. Subsequently, CWP was calculated by dividing the total seasonal yield by the corresponding seasonal AET for each crop and season. For berseem, both crop yield and CWP values were further multiplied by 0.14 to convert from fresh to dry biomass values (Dost et al., 2014).

Table 4.2. Crop parameters used for each crop in this study.

Parameter	Wheat	Berseem (fresh)	Rice	Maize
Light use efficiency (a)	2.5 g MJ^{-1} (Hatfield and Dold, 2019; Pradhan et al., 2018)	1.8 g MJ^{-1} (b) (Hatfield and Dold, 2019; Steduto et al., 2012)	2.2 g MJ^{-1} (Fu et al., 2021; Hatfield and Dold, 2019; Liu et al., 2020)	3.8 g MJ^{-1} (Hatfield and Dold, 2019; Lindquist et al., 2005)
Light use efficiency correction factors	0.93 (C3) (Sadras et al., 2016; Wang et al., 2012)	0.66 (C3) (b) (Sadras et al., 2016; Wang et al., 2012)	0.82 (C3) (Sadras et al., 2016; Wang et al., 2012)	1.4 (C4) (Sadras et al., 2016; Wang et al., 2012)
Harvest index	0.5 (El Hawary et al., 2015; Kheir et al., 2021b)	0.95 (b) (FAO, 2023c; Sadras et al., 2016)	0.48 (Mousa and Abdelghany, 2022)	0.4 (Kandil, 2013; Salama et al., 2021)
Aboveground over total biomass	0.9 (El Hawary et al., 2015)	0.9 (a) (Giambalvo et al., 2011)	0.8 (Mekawy et al., 2015; Nada and Abogadallah, 2018)	0.92 (a) (Ordóñez et al., 2020)
Moisture content (%)	14 (El-Porai et al., 2013)	86 (Dost et al., 2014; Salama et al., 2020)	14 (Hafez et al., 2021)	15 (Amer, 2010; El-Hendawy et al., 2008)

[a] values from other countries since the specific value in Egypt was not available. [b] taken for Alfalfa since values for berseem could not be found.

4.2.6. Benchmarking potential improvements of performance indicators

Benchmarking involves estimating average values of performance indicators and identifying higher achievable values of these indicators within Zankalon. We analyzed the 5-year average values of performance indicators and set upper threshold percentiles to gauge potential improvements (Fig. 4.2b). The selection of upper threshold percentiles vary among studies, typically ranging from 70 to 95% (Licker et al., 2010; Mekonnen et al., 2020; Mekonnen and Hoekstra, 2014; Safi A. et al., 2022; Zwart and Bastiaanssen, 2004). We calculated three threshold percentiles at 80, 90, and 95% to provide insights into scenarios of higher potential improvements. Subsequently, we expressed these three potential improvements as percentages relative to the averages rather than absolute values (Eq. 4.3; Fig. 4.2: step #3).

$$Potential\ improvements_{Zankalon} = \frac{Threshold\ percentiles\ (80,90,95\%) - average\ value}{average\ value} \times 100 \qquad (4.3)$$

The choice of presenting potential improvements in percentage terms was driven by two considerations. First, it acknowledges that absolute values would exclusively reflect the Zankalon region as part of the Delta’s old lands. Second, it mitigates reliance on WaPOR’s accuracy in estimating performance indicators, as the possibility of systematic under- or overestimation for certain parameters exists (Blatchford et al., 2020; FAO, 2020b; McNamara et al., 2021; Weerasinghe et al., 2020). The identified percentage improvements were used to model future water and land demand for four crops at the national level (Fig. 4.2c).

To explore the variability of performance indicators in Zankalon further, we calculated spatial and temporal coefficients of variation (CV = standard deviation/mean) for each indicator over the period 2016–2021. Temporal CV measures the interannual variation across the 5-year time series, while spatial CV indicates spatial variability across cropland pixels on the 5-year average maps.

4.2.7. Scenario development

To build future scenarios for all Egypt based on calculated performance indicators and potential improvements detected in Zankalon, a comprehensive analysis of domestic crop production and population growth is essential. Consequently, we obtained time series of historical and forecasted total population (medium fertility variant) as well as crop statistics, including cultivated area, yield, and production quantities of the studied crops at the national level of Egypt (Table 4.1).

Based on available data, the periods 2000–2020 for rice, maize, and wheat, and 2004–2020 for berseem, were selected to estimate the average per capita domestic production of each crop in kg/capita/year (Eq. 4.4). Next, we calculated future demand for each crop to be produced domestically in Egypt from 2021 through 2050 (Eq. 4.5, Fig. 4.2: step #4).

$$Per\ capita\ domestic\ production_{\ 2000-2020} = \frac{Annual\ domestic\ production}{population} \qquad (4.4)$$

$$Future\ demand\ for\ crop_{\ 2021-2050} = per\ capita\ production_{\ 2000-2020} \times population_{\ 2021-2050} \quad (4.5)$$

To calculate future water and land demands of the four crops in all Egypt, it was imperative to compute representative values for crop yield, CWP, and T/AET at the national scale. In the absence of T/AET values in literature sources, we used values resulting from the Zankalon analysis (2016–2021) to represent potential improvements at the national level of Egypt. Average national crop yield values were calculated for each crop using recent data from FAOSTAT and CAPMAS over 2016–2020 (Eq. 4.6).

$$Average\ national\ crop\ yield = \frac{Annual\ domestic\ production}{Harvested\ area} \qquad (4.6)$$

For CWP, we synthesized representative values from studies covering the national scale and calculated the average value for each crop (Table 4.3). Subsequently, average national values for yield, CWP, and T/AET were factored by the percentages of potential improvements as identified in Zankalon to estimate the three potential values of the three indicators at the national level (Eq. 4.7, Fig. 4.2: step #5).

$$Potential\ indicator\ value_{Egy} = averages_{Egy} \times [(100 + potential\ improvements_{Zankalon})/100] \quad (4.7)$$

Table 4.3. Values for crop water productivity of the studied crops in Egypt.

Crop	Value (kg/m^3) [(a)]	Time coverage	Source
Wheat	0.87	2015–2019	(Swelam et al., 2022)
	1.6	2017–2018	(El-Marsafawy and Mohamed, 2021)
	1.1	2017	(Nikiel and Eltahir, 2021)
	1.8 [(b)]	2020	(CAPMAS, 2023)
	1.34	Average used in this study	
Berseem (dry)	1.4	2017	(Nikiel and Eltahir, 2021)
	2.5 [(b)]	2020	(CAPMAS, 2023)
	1.95	Average used in this study	
Maize	0.65	2015–2019	(Swelam et al., 2022)
	1.0	2017–2018	(El-Marsafawy and Mohamed, 2021)
	1.0	2017	(Nikiel and Eltahir, 2021)
	1.1 [(b)]	2020	(CAPMAS, 2023)
	0.94	Average used in this study	
Rice	1.1	2017–2018	(El-Marsafawy and Mohamed, 2021)
	1.0	2017	(Nikiel and Eltahir, 2021)
	1.3 [(b)]	2020	(CAPMAS, 2023)
	1.13	Average used in this study	

[a] some values were obtained from graphs in their corresponding studies or derived thus minor deviations may exist. [b] values scaled by field irrigation efficiency of 70%.

Future land demand (in ha) for each crop from 2021 through 2050 was calculated based on the average and the three potential improvements in crop yield (Eq. 4.8), resulting in four land demand scenarios for each crop (Land-1, 2, 3, and 4; Fig. 4.2: step #6).

$$Future\ land\ demand_{Land\text{-}1,2,3,4} = \frac{Future\ demand\ for\ crop}{average\ and\ potential\ yield\ values} \quad (4.8)$$

Future water demand was calculated in seven scenarios. One scenario (Water-1) was calculated based on the average values of CWP and T/AET, implying the continuation of current average values in the future (Eq. 4.9). Three scenarios (Water-2. 3, and 4) were calculated based on three potential CWP values (Eq. 4.10). Three more scenarios (Water-5. 6, and 7) were based on potential values of both CWP and T/AET to account for additional water savings in each scenario and crop associated with the combined influence of improvements of CWP and T/AET (Eq. 4.11). This resulted in seven scenarios of water demands for each crop (Water-1 to 7; Fig. 4.2: steps #7 and #8). In all water scenarios, we scaled water demand values by both field irrigation and conveyance efficiencies to estimate the total irrigation water demand at High Aswan Dam (HAD) (Fig. 4.1a). Here, irrigation efficiency refers to the ratio of water supplied to fields to the actual water consumed by crops, whereas conveyance efficiency is the ratio of water supplied to fields to the water quantities released at HAD for irrigation needs. In Egypt, field irrigation efficiency ranges from 60 to 70% (Abdelkader et al., 2018; Ayyad et al., 2019; Elsayed et al., 2022b; Nikiel and Eltahir, 2021). Since the analysis focuses on future scenarios, we chose an irrigation efficiency of 70%. Additionally, based on data from CAPMAS for the period 2016–2021, we estimated a conveyance efficiency of approximately 85%.

$$Future\ water\ demand_{Water\text{-}1} = \frac{Future\ demand\ for\ crop}{Average\ CWP\ and\ T/AET\ values} \times 0.7 \times 0.85 \quad (4.9)$$

$$Future\ water\ demand_{Water\text{-}2,3,4} = \frac{Future\ demand\ for\ crop}{Potential\ CWP\ values} \times 0.7 \times 0.85 \quad (4.10)$$

$$Future\ land\ demand_{Water\text{-}5,6,7} = \frac{Future\ water\ demand_{water-2,3,4}}{Potential\ T/AET\ values} \quad (4.11)$$

4.2.8. Scenario assumptions

In constructing future scenarios, the following key assumptions were made:

- We based our scenarios on the population forecast of the medium fertility variant, excluding the high and low fertility variants (United Nations, 2023b).
- The existing import and export ratios of the studied crops were assumed to remain constant until 2050. Here, our modelling approach and the scenarios proposed are concerned with the potential improvements in domestic production and thus trade activities were excluded.
- The per capita average domestic production from 2000 to 2020 was considered to remain unchanged until 2050. Changes in socioeconomic indicators, such as per capita GDP, may influence the per capita demand of some food commodities. While berseem's demand is not tied to GDP, lower correlations were found between per capita GDP and demand for rice ($R^2 = 0.2$) and wheat ($R^2 = 0.5$) than for maize ($R^2 = 0.8$) over the last decades in Egypt (Nikiel and Eltahir, 2021). Maize's high correlation with GDP can be attributed to its use as animal feed embedded in meat products that have a strong relationship with GDP (Nikiel and Eltahir, 2021). Nevertheless, the aforementioned correlations are concerned with the total per capita supply of these crops (both imported and domestically produced) while our analysis focuses only on the per capita portion that is domestically produced, which rather reflects the country's agricultural production capacity, thus assuming the average of 2000–2020 to remain constant through 2050.
- Climate change and its impacts on crop water requirements, crop productivity, sea level rise, saltwater intrusion, and future Nile water availability and variability were not analyzed in this study.

These assumptions were also made in a similar assessment by Ayyad and Khalifa (2021) and should be considered when interpreting the results and their applicability to real-world conditions.

4.3. Results

4.3.1. Absolute values of performance indicators

The seasonal and 5-year average estimates of performance indicators for each crop as derived from WaPOR over Zankalon during the period 2016–2021 are presented in Fig. 4.3, 4.4, and 4.5. The T/AET values for all crops in all years were relatively high (≥0.79) (Fig. 4.3). In terms of crop yield and CWP, the 5-year average values stood at 1.5, 1.8, 6.3, and 9.2 t/ha and 0.2, 0.3, 1.05, and 1.2 kg/m^3 for rice, maize, wheat, and berseem (dry), respectively (Fig. 4.4 and 4.5). It is worth noting that the yield and CWP values for rice and maize, both summer crops, are significantly lower than commonly reported values in the existing literature (Section 4.4.1 provides further insights). The figures for actual evapotranspiration and transpiration can be found in Appendix A (Fig. A1 and A2).

Across all crops, the analysis of 5-year average maps unveiled limited spatial variations across the crop pixels in Zankalon (Figures 4.3b, 4.4b, and 4.5b). Spatial CV values for all indicators were lower than 20% (Table 4.4). Similarly, notably low interannual variations were observed in all studied indicators, as indicated by the low values of temporal coefficients of variation (CV < 10%) (Table 4.4).

Table 4.4. Spatial and temporal coefficient of variation (CV) of the performance indicators in Zanaklon.

Indicator	CV (%)	Rice	Maize	Wheat	Berseem
Crop yield	Temporal	9	4	2	3
	Spatial	18	14	11	9
Crop water productivity	Temporal	7	5	4	6
	Spatial	8	7	5	5
Transpiration fraction	Temporal	2	2	1	1
	Spatial	4	3	2	1
Actual evapotranspiration	Temporal	6	4	6	5
	Spatial	13	10	8	7
Transpiration	Temporal	6	3	5	5
	Spatial	15	11	9	8

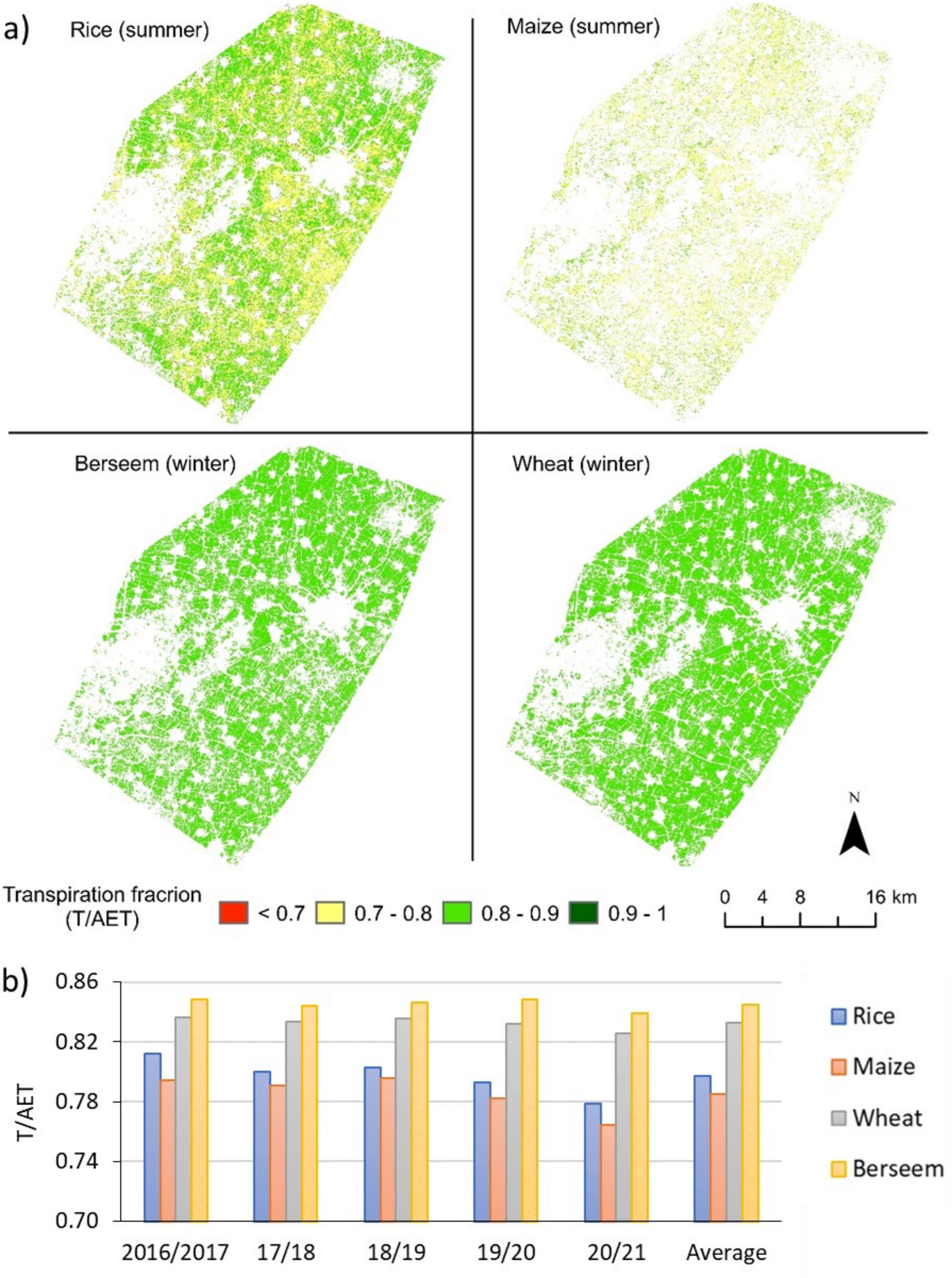

Fig. 4.3. a) Spatial variation of seasonal transpiration fraction (T/AET) for the studied crops in Zankalon (average of 2016–2021). b) Seasonal and 5-year average estimates. Data derived from WaPOR.

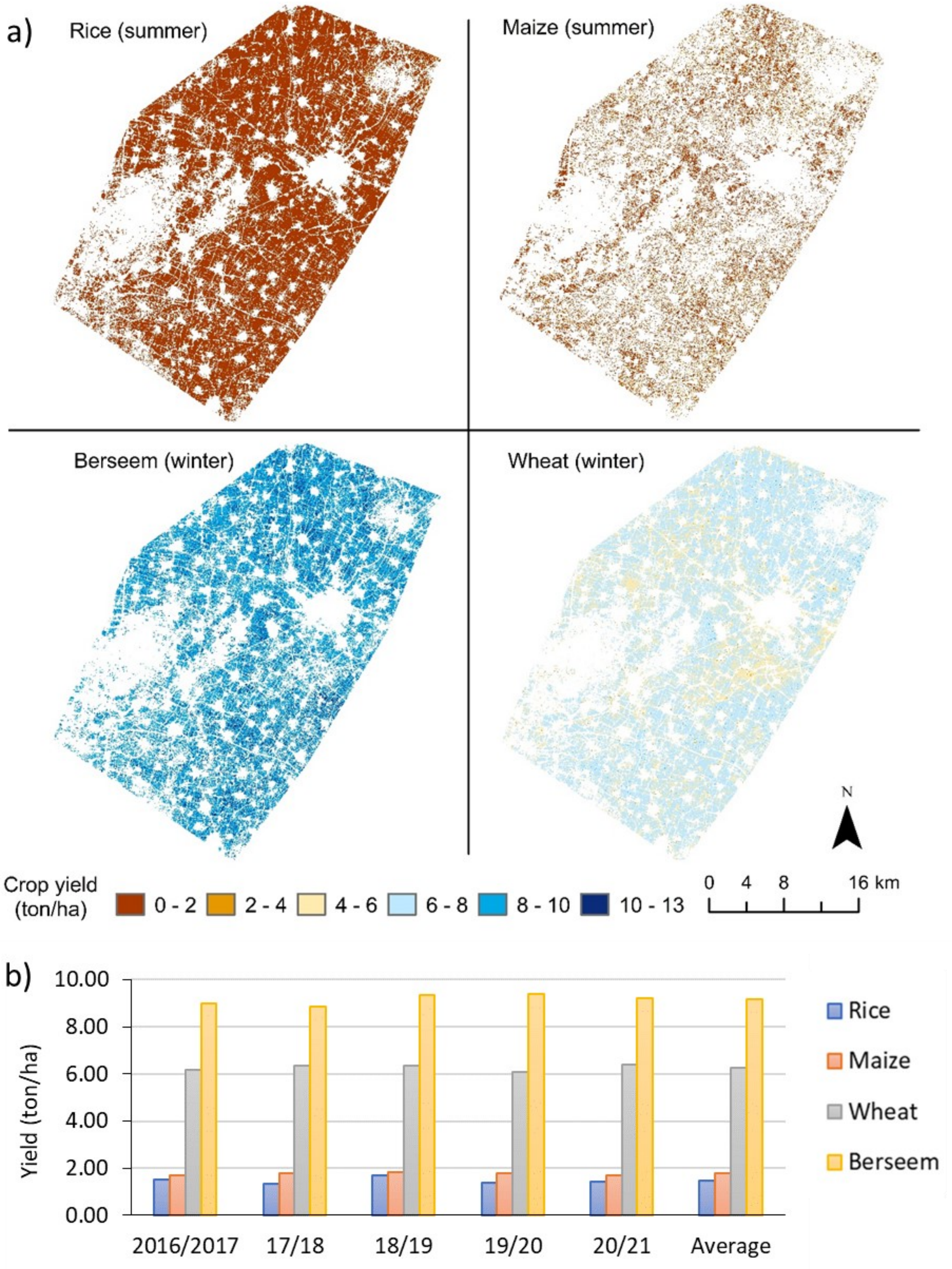

Fig. 4.4. a) Spatial variation of seasonal crop yield for the studied crops in Zankalon (average of 2016–2021). b) Seasonal and 5-year average estimates. Data derived from WaPOR.

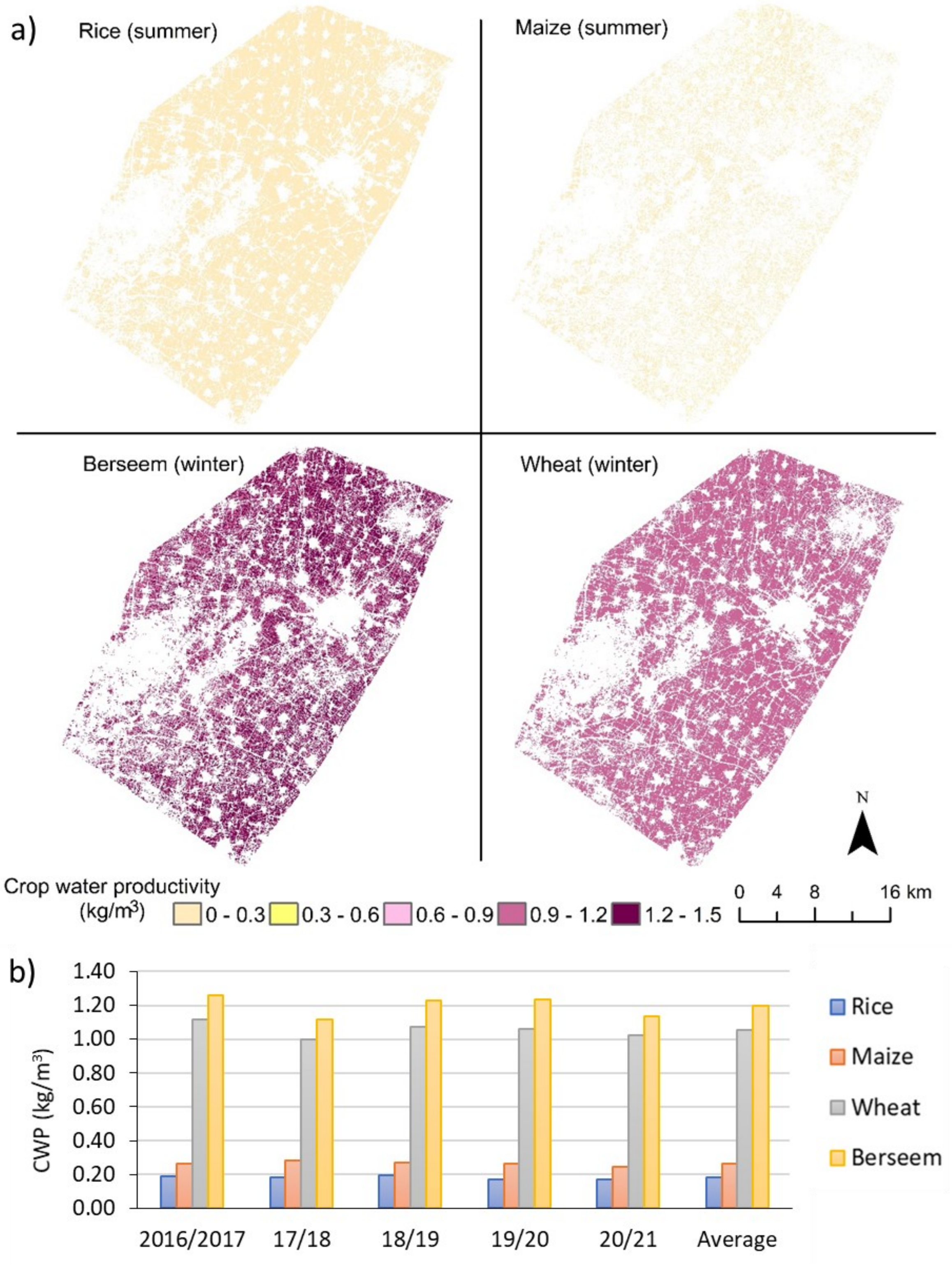

Fig. 4.5. a) Spatial variation of seasonal crop water productivity (CWP) for the studied crops in Zankalon (average of 2016–2021). b) Seasonal and 5-year average estimates. Data derived from WaPOR.

4.3.2. Percentages of potential improvements in Zankalon and their national extrapolation

The percentages denoting potential improvements for crop yield, T/AET, and CWP in Zankalon for the four crops are shown in Table 4.5. Notably, T/AET values exhibited limited potential for improvements since relatively high values were observed. The T/AET for rice and maize showed the highest percentage of improvements of 4% at percentile 95%. In contrast, the potential improvements for crop yield were substantially higher. Winter and summer crops demonstrated the capacity to enhance yield values by up to 17 and 27%, respectively, at percentile 95%. Similarly, CWP followed a comparable pattern at percentile 95%, with potential improvements of up to 10 and 14% for winter and summer crops, respectively. These percentages of potential improvements for yield, T/AET, and CWP in Zankalon were subsequently used to gauge the potential impacts of these improvements at the national scale of Egypt. Table 4.5 shows the average values for yield, T/AET, and CWP between 2016–2020 for each crop at the national level and the potential values based on the extrapolated percentages of improvements.

4.3.3. Future demand for crops

In accordance with the UN population forecast, the Egyptian population has seen an increase from 70 million capita in 2000 to 106 million capita in 2020. This trend is projected to continue, reaching about 160 million capita by 2050, following the medium fertility variant (Fig. 4.6).

The average per capita domestic production of rice, maize, wheat (2000–2020), and berseem (2004–2020) were 66, 82, 93, and 75 kg/capita/year, respectively. To sustain this production by 2050, Egypt would need to produce approximately 11, 13, 15, and 12 million tons of rice, maize, wheat, and berseem, respectively (Fig. 4.6). In other words, production quantities would need to increase by 128, 78, 69, and 71% above the 2016–2020's average production quantities for rice, maize, wheat, and berseem, respectively.

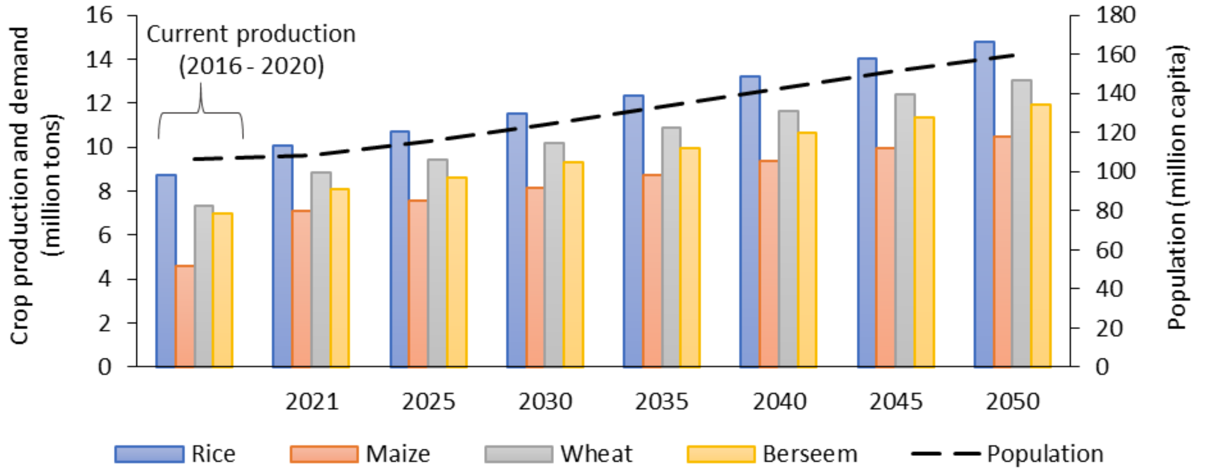

Fig. 4.6. Relation between population growth (2020–2050), current crop production quantities (2016–2020), and estimated crop demand (2021–2050).

Table 4.5. Percentages of potential improvements for transpiration fraction (T/AET), crop yield, and crop water productivity (CWP) for the studied crops in Zankalon as derived from WaPOR (2016–2021) and the average and potential values for yield, T/AET, and CWP values between 2016–2020 for each crop at the national level.

Indicator	Levels	Unit	Rice	Maize	Wheat	Berseem
T/AET (Zankalon)	Improvements at percentile 80%	%	2	2	1	1
	Improvements at percentile 90%		3	3	2	1
	Improvements at percentile 95%		4	4	2	2
Yield (Zankalon)	Improvements at percentile 80%	%	14	11	8	7
	Improvements at percentile 90%		21	17	12	12
	Improvements at percentile 95%		27	22	17	16
CWP (Zankalon)	Improvements at percentile 80%	%	6	6	4	4
	Improvements at percentile 90%		9	9	6	7
	Improvements at percentile 95%		14	13	10	9
T/AET (Egypt)	Average value	Dimensionless	0.79	0.79	0.83	0.84
	Value at percentile 80%		0.81	0.80	0.84	0.85
	Value at percentile 90%		0.82	0.81	0.85	0.86
	Value at percentile 95%		0.83	0.82	0.85	0.86
Yield (Egypt)	Average	t/ha	9.1	7.1	6.5	10.5
	Value at percentile 80% [(a)]		10.4	7.9	7.1	11.2
	Value at percentile 90%		11	8.3	7.3	11.7
	Value at percentile 95%		11.6	8.7	7.6	12.2
CWP (Egypt)	Average	kg/m^3	1.1	0.94	1.3	1.9
	Value at percentile 80%		1.20	1	1.39	2.02
	Value at percentile 90%		1.24	1.02	1.42	2.08
	Value at percentile 95%		1.30	1.06	1.47	2.12

4.3.4. Future demand for land and water

To sustain domestic production of the four crops by 2050, following the average yield values in Land-1 scenario, a cultivated land area of approximately 6.4 million hectares (Mha) would be required. However, if the average yield values were to increase to reach the 80, 90, and

95% percentile values as in Land-2, Land-3, and Land-4 scenarios, the total land area needed to cultivate these four crops in 2050 would drop to 5.8, 5.5, and 5.3 Mha, respectively. In all scenarios, the total land area required are distributed among rice (18%), maize (28%), wheat (36%), and berseem (18%). For instance, the required 6.4 Mha by 2050 in Land-1 scenario would be distributed between rice (1.15 Mha), maize (1.85 Mha), wheat (2.25 Mha), and berseem (1.15 Mha). Fig. 4.7 shows the land areas required for each scenario from 2021 through 2050, illustrating how changes in yield values can affect the overall land area required for crop cultivation.

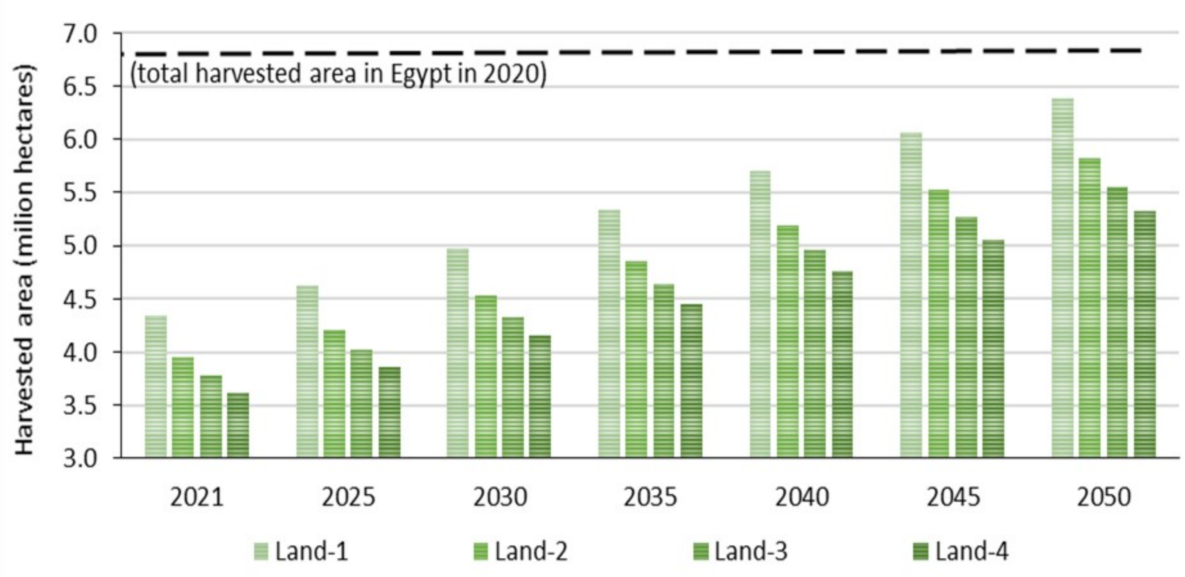

Fig. 4.7. The estimated future land area required in the developed scenarios to sustain production of rice, maize, wheat, and berseem in Egypt from 2021 through 2050. Land-1 implies continuation of average crop yields. Land-2. 3, and 4 imply higher crop yields based on three potential improvements as explained in Section 4.2.7.

The water quantities required from 2021 through 2050 to cultivate the four crops in each scenario, taking both the irrigation and conveyance efficiencies into account, are shown in Fig. 4.8. Under the average scenario for CWP and T/AET, (Water-1 scenario) a total water quantity of 68 billion cubic meters (BCM) would be needed to sustain the production of the four crops by 2050. If we transition to higher CWP levels as in Water-2, Water-3, and Water-4 scenarios, the total water demand would decrease to 65, 63, and 61 BCM, respectively. When considering the combined influence of improvements of CWP and T/AET, the water demand by 2050 would decrease to 64, 61, and 59 BCM in Water-5, Water-6, and Water-7, respectively. In all scenarios, about 23%, 34%, 28%, and 15% of the total water demand are distributed among rice, maize, wheat, and berseem, respectively. For instance, the required 68 BCM by 2050 in Water-1 scenario would be distributed between rice (15.5 BCM), maize (23.5 BCM), wheat (18.5 BCM), and berseem (10.5 BCM).

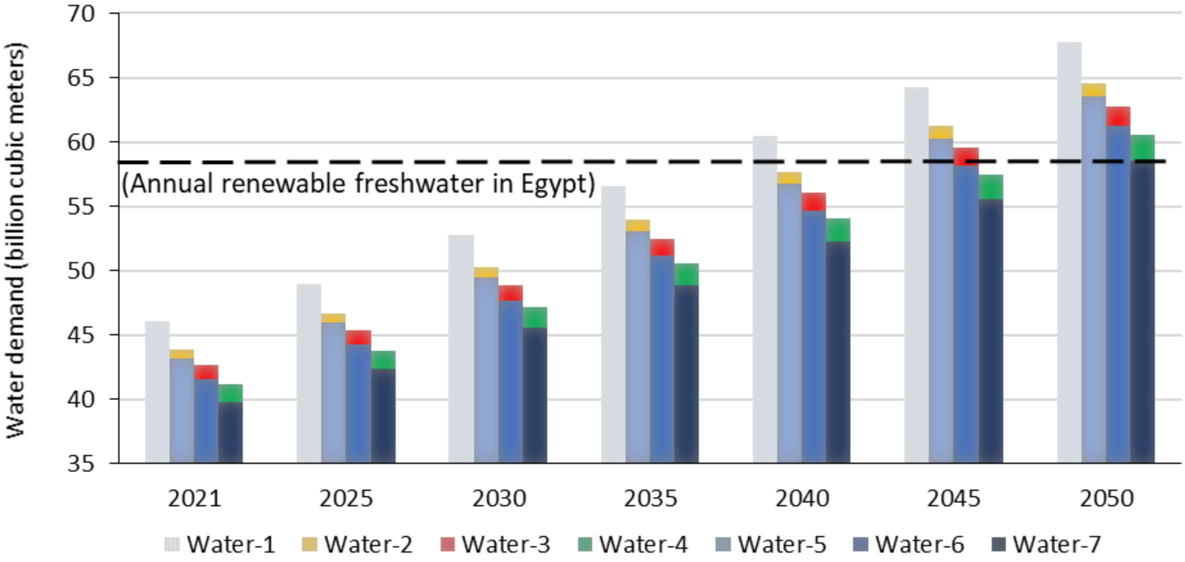

Fig. 4.8. The estimated future water quantities required in the developed scenarios to sustain production of rice, maize, wheat, and berseem in Egypt from 2021 through 2050. Water-1 implies continuation of average values of crop water productivity and transpiration fraction. Water-2, 3, and 4 imply higher values of crop water productivity. Water-5, 6, and 7 imply higher values of both crop water productivity and transpiration faction as explained in Section 4.2.7.

4.4. Discussion

4.4.1. Suitability of WaPOR datasets

To assess the reliability of the WaPOR datasets used in this study, the derived values of performance indicators over Zankalon were compared to their counterparts reported in literature. The differences in research methodologies used, lengths of growing season, spatial and temporal coverage in each study are the main drivers for disparities between findings.

4.4.1.1. Actual evapotranspiration

Our study estimated 5-year average seasonal AET values for rice (807 mm/season), maize (660 mm/season), wheat (595 mm/season), and berseem (767 mm/season) in Zankalon. These values closely align with findings by El-Agha et al. (2011), who estimated AET of 779, 740, 634, and 746 mm/season, for rice, maize, wheat, and berseem, respectively, utilizing remote sensing data during the 2008–2009 growing season in the central Nile Delta. Another study by El-Kilani and Sugita (2017) reported average AET values (2010–2014) from an experimental station in Zankalon of 667, 369, 431, and 366 mm/season, for rice, maize, wheat, and berseem, respectively. The significant disparity between the AET values reported by El-Kilani and Sugita (2017) and our study can be attributed to the difference in the assumed length of the growing season. They assumed growing seasons of about 30 days shorter than our detected lengths. Nevertheless, this comparison implies the possible overestimation of

WaPOR's AET values over Zankalon, in line with previous conclusions of WaPOR's tendency to overestimate AET over small irrigated fields similar to Zankalon (Blatchford et al., 2020).

4.4.1.2. Crop yield and water productivity

The estimated yield and CWP values for wheat (6.3 t/ha and 1.05 kg/m^3) and berseem (9.2 t/ha and 1.2 kg/m^3) compared well with reported values in other studies. For instance, El-Agha et al. (2011) reported yield of 6 t/ha and CWP of 1.05 kg/m^3 for wheat in the central Nile Delta during 2008–2009, which closely match our estimated values. Moreover, based on CAPMAS data during 2016–2020, the average yield values for wheat and berseem were 6.4 and 10.4 t/ha in the governorate of Sharkia where Zankalon is located. Our recorded yield value for berseem is also in close agreement with the 70 t/ha fresh yield (equivalent to 9.8 t/ha dry yield) reported by Dost et al. (2014). Additionally, Kheir et al. (2021c) calculated CWP for wheat of about 1.5 kg/m^3 in Sharkia for the period 1991–2020. Swelam et al. (2022) estimated CWP of 1.08 kg/m^3 for wheat in the Delta's old lands from 2015 to 2019. These comparisons reaffirm the validity and accuracy of WaPOR's estimates of yield and CWP for winter crops in Zankalon.

Our estimates of yield and CWP for summer crops in Zankalon, rice (1.45 t/ha and 0.18 kg/m^3) and maize (1.8 t/ha and 0.27 kg/m^3), revealed a substantial underestimation compared to values reported in other studies over the Nile Delta. To elaborate, our estimated yield values significantly deviate from the average value of 8.2 and 8.5 t/ha for rice and maize, respectively, obtained in Sharkia during the period 2016–2020 (CAPMAS, 2023). Consequently, the estimated CWP values for rice and maize in Zankalon are significantly underestimated. In the Nile Delta, El-Agha et al. (2011) estimated a CWP of 1.04 kg/m^3 for rice during 2008–2009 and Swelam et al. (2022) calculated CWP for maize of 0.95 kg/m^3 during the period 2015–2019. The underestimation of yield values is attributed to the concurrent underestimation of Net Primary Productivity (NPP) during the summer season (Fig. 4.2a). WaPOR's NPP algorithm incorporates various stress factors, including soil moisture, vapor pressure deficit, and temperature. WaPOR's notable underestimation of NPP for summer crops in hot arid areas is driven by the temperature stress, resulting in observed crop stress through NPP that does not align with the actual conditions on the ground (FAO, 2020b). Consequently, we regard WaPOR as unsuitable for estimating absolute values of yield and CWP for summer crops in irrigated arid regions similar to Zankalon.

4.4.2. Performance indicators

4.4.2.1. Egypt's stand on the global spectrum

The average yields in Egypt of 9.0, 7.2, and 6.5 t/ha for rice, maize, and wheat, respectively, from 2016 to 2020 underscore Egypt's standing among the world's highest crop yield producers. During the same period, the global average yield for rice, maize, and wheat were notably lower at 4.6, 5.8, and 3.5 t/ha, respectively (FAOSTAT, 2023). Furthermore, the average national CWP values for wheat (1.3 kg/m^3), rice (1.1 kg/m^3), and maize (0.95 kg/m^3) (Table 4.3), fall within the global high ($\geq$ 1.10 kg/m^3), medium (0.70 to 1.25 kg/m^3), and low ($\leq$ 1.25 kg/m^3) categories, respectively, as classified by Foley et al. (2020). While the Egyptian CWP for rice and wheat surpass the global average values for rice (0.95 kg/m^3) and wheat (0.92 kg/m^3), CWP for maize in Egypt remains significantly lower than the global average of 2.25 kg/m^3 (Bastiaanssen and Steduto, 2017). While these comparisons highlight Egypt's exceptional crop yield performance and relatively efficient water use practices in the cultivation of rice and wheat, they unravel the potential to improve CWP of maize, through optimizing maize's water use as the driver for the low CWP values in Egypt.

The estimated T/AET values of cropland in Zankalon ($0.79 \leq T/AET \leq 0.84$) are notably positioned on the higher spectrum of reported T/AET values in literature. For instance, T/AET values stand at 0.66–0.72 over croplands globally (Wang-Erlandsson et al., 2014; Wei et al., 2017), and at 0.67 (±0.04) for maize, 0.65 (±0.07) for wheat, and 0.57 (±0.02) for rice over typical croplands in North America, Europe and Asia, as reported by Jiang et al. (2020).

4.4.2.2. Performance variation and potential for improvements in Zankalon

The findings presented in Section 4.3.1 reveal the limited spatial and temporal variation observed for the studied crops and indicators in Zankalon. For instance, according to Molden and Gates (1990), spatial variation as expressed by the coefficient of variation of AET (spatial CV), also known as the uniformity indicator of water use (Karimi et al., 2019), of 0–10%, 10–25%, and > 25% imply good, fair, and poor uniformity in water use, respectively. In Zankalon, spatial CV values of AET for all crops were between 7 and 13%. Similarly, the limited interanuual variation of the studied indicators and crops in Zankalon is close to that of all cropland in Egypt (temporal CV < 10%) (Ayyad and Khalifa, 2021). This suggests a high degree of stability of performance indicators over time and across the fields.

The percentile analysis is a valuable tool for determining which crops and performance indicators should be prioritized when planning interventions. The findings in Section 4.3.2 serve as pivotal entry points for guiding interventions and investments to enhance crop production and conserving vital water and land resources. For instance, when examining results of T/AET, it becomes evident that there is limited potential for improvement, as the values were notably high, i.e., achieving the 95% percentile values translates to only 2–4% improvements. Therefore, focusing on enhancing T/AET may be less pressing than other potential interventions. On the contrary, striving to reach the 95% percentile values for CWP and crop yield emerges as a more compelling course of action (improvements of 9–14% for CWP and 16–27% for yield). In general, implementing interventions to improve performance indicators, i.e., achieving higher percentile values, will benefit more the summer (rice and maize) than the winter crops (wheat and berseem) at the same percentile level. These findings emphasize the potential for crop intensification in Zankalon.

4.4.3. What can Egypt do?

The projected future demand for the studied crops in this study, along with the associated water and land requirements to sustain their production, confirm conclusions made by relevant studies indicating the forthcoming challenge for Egyptian decision makers (Asseng et al. 2018; Abdelkader et al. 2018; Abdelaal and Thilmany 2019; Ayyad and Khalifa 2021; Nikiel and Eltahir 2021). To further explain, the estimated total water demand of the four crops by 2050 in the most optimistic scenario of 59 BCM is equal to the annual total renewable freshwater of the country. Similarly, the optimistic 5.3 Mha of harvested area required to sustain production of the four crops by 2050 translates to 78% of the country's total harvested area (CAPMAS, 2023). However, our findings highlight the potential for conserving 9 BCM of water and 1.1 Mha of land by implementing highly efficient scenarios. In this section, we propose a set of strategies to enable Egypt coping with the future challenge of sustaining supply of these crops with its limited natural resources. Since our findings essentially indicate the gap between the supply capacity and demand for the four crops, the following discussion focuses on possible interventions on the supply and demand sides to minimize this gap. These interventions are grouped to target (i) improving the productivity of farming systems (crop supply side and demand for resources), (ii) curbing the continuous rise in crop demand (crop demand side), and (iii) broader interventions (resources management).

4.4.3.1. Improving productivity of farming systems

Our findings indicate the existing opportunity to enhance crop yield and water productivity of the four crops by achieving higher existing levels. Adopting appropriate crop management practices can enable improve the crop yield and water productivity, and thus help close the gap between the average and potential levels. This is particularly crucial for maize and wheat as the most demanding crops for water and land by 2050.

For instance, efficient deficit irrigation strategies can improve yield and water productivity of maize in Egypt (e.g., Attia et al., 2021; El-Sanatawy et al., 2021). Farming practices including weed control (Saudy and El–Metwally, 2023), seed priming (El-Sanatawy et al., 2021), partial soil drying and organic mulching (Abdelraouf and Ragab, 2018), double ridge-furrow planting technique (Abd El-Halim and Abd El-Razek, 2014), silicate foliar application and optimal irrigation intervals (Gomaa et al., 2021; Kandil et al., 2023) can also increase yield and water productivity of maize. Adjusting the sowing dates based on the specific location reportedly improves maize productivity (Abaza et al., 2023). In particular, raised beds appear to be an important strategy that could save about 20% of applied water in maize cultivation (Elmahdy et al., 2023).

The use of raised beds is also valuable in irrigated wheat fields, which has been shown to reduce water consumption and increase yield by up to 25% (Alwang et al., 2018; Rady et al., 2021; Yigezu et al., 2021a). Deficit irrigation and nitrogen applications can maximize wheat yield and water productivity (Kheir et al., 2021b, 2021c). The use of drip irrigation and compost applications positively impacts yield and water productivity of wheat in newly reclaimed sandy soils (Alshallash et al., 2023). Under stress and saline conditions, the use of salicylic acid improves wheat yield and water productivity (Hafez and Farig, 2019). Different irrigation strategies and frequencies are considered the most yield-effective production factor, explaining nearly 40% of the yield variability in parts of the Delta’s old lands (Abdalla et al., 2023). The use of tridimensional uniform sowing mode and the development of wheat varieties that are resistant to rusts and abiotic stress could further enhance future wheat yield (Abdelmageed et al., 2019).

Using wide furrows for rice cultivation can improve rice yield and water productivity (Mahmoud et al., 2016). Substituting some cultivars with high-yielding and water-saving ones has the potential to increase land productivity by up to 23% (Mehana et al., 2021) and save up about 20% of irrigation water (Elmoghazy and Elshenawy, 2019). For berseem, the choice of cultivars, cutting management, sowing date, fertilizer applications, and mixture with other crops can significantly improve the yield (Dost et al., 2014; Salama, 2020; Salama et al., 2020). In general, appropriate crop rotations in the Egyptian farming systems can improve crop growth and productivity (Abdalla et al., 2023; Said et al., 2016; Salama et al., 2021).

4.4.3.2. Curbing the continuous rise in crop demand

The rise in crop demand estimated in this study is mainly a function of population growth and dietary preferences. On the one hand, bending the population growth curve will help reducing the future demand for all crops and their associated water and land requirements in Egypt.

We calculated future crop demands based on the medium fertility variant, projecting a population of 159 million capita by 2050. Following the milder population growth scenario of low fertility variant at 147 million capita (United Nations, 2023b) would reduce the demand for crops and their associated water and land requirements by about 8%. One the other hand, promoting changes in dietary habits appear as a reasonable response to lessen the heavy reliance on the four studied crops. For example, the high demand for maize and berseem is due to their use as animal feed for meat production. Therefore, a gradual change in the dietary patterns, by transitioning from the current meat-based to a more plant-based diet, presents opportunities to reduce future demand for these crops in Egypt (Abdelkader et al., 2018; Nikiel and Eltahir, 2021; Terwisscha van Scheltinga et al., 2021). Another opportunity to conserve water and land resources is represented by the substitution of portions of major cereal crops, particularly wheat. For instance, portions of wheat flour can be substituted with less water-intensive alternatives when producing staple commodities such as the Egyptian Balady bread (Soliman et al., 2019). Furthermore, changing dietary preferences would allow for wider crop substitution scenarios towards reducing the high dependency on water-intensive crops. Examples include the substitution of wheat and rice with less water-intensive crops such as millet and sorghum, without compromising the nutritional values (Chakraborti et al., 2023; Davis et al., 2018).

4.4.3.3. Broader interventions

There exist further opportunities to bridge the gap between resources availability and demand in Egypt. For instance, reducing food waste and losses can mitigate the high crop demand and associated resources. According to Yigezu et al. (2021b), Egypt experiences particularly high losses and wastage in wheat, accounting for around 20% of both domestically produced and imported wheat. Eliminating part of these losses would conserve water and land required to sustain domestic production.

While our results indicate relatively high values for performance indicators in Egypt, there is still room for improvement in both field and conveyance efficiencies of 70 and 85%, respectively, adopted in our analysis (Brouwer et al., 1989). Initiatives aimed at replacing traditional irrigation methods with modern systems and rehabilitation of irrigation canals to improve the overall system efficiency should continue. Nevertheless, risks of increased soil and groundwater salinity and reduced groundwater recharge should be considered. Although the Nile will continue to serve as Egypt’s primary source of freshwater, the increasing water demand necessitates the exploration of non-conventional water resources. Domestically, Egypt should intensify its efforts in water reuse, wastewater treatment, and desalination.

Exploiting non-renewable groundwater resources should be approached cautiously to avoid further groundwater depletion and salinization (El-Agha et al., 2023).

Except for berseem, Egypt is currently a net importer of the studied cereal crops (FAOSTAT, 2023). Given the expected continuation of cereal imports, Egypt should critically assess its trade activities, evaluating not only the feasibility, efficiency, and profitability of producing its major cereals domestically but also scrutinizing existing trade partnerships. For example, berseem and at least 20% of maize domestic productions are used as animal feed in Egypt (FAOSTAT, 2023), and reducing the domestic production of these crops can conserve water and land resources. Instead of allocating about 14 BCM of water and 1.3 Mha of harvested land to sustain berseem and maize production used for meat production by 2050 as estimated herein, Egypt could import part of its meat demand from neighboring countries such as Sudan and Ethiopia. This approach not only can conserve water resources and free up fertile land but also presents an opportunity to foster mutually-beneficial ties with Nile riparian nations (Ayyad and Khalifa, 2021; Nikiel and Eltahir, 2021). Collaborating with the Nile countries should further aim at enhancing the low crop yield and water productivity of cereal crops coupled with transboundary trade (Ayyad and Khalifa, 2021; Siderius et al., 2016; Zeitoun et al., 2010), and minimizing water losses across the entire basin that can consequently increase blue water availability for irrigation downstream the Nile.

4.4.4. Methodological learnings

One of the novel contributions of this study is the developed methodological approach, which is also beneficial to other regions with similar conditions to Egypt. We demonstrated how integrating multiple types of open-access datasets in data-scare regions, including remote sensing and crop statistics with different spatial and temporal coverages, can help quantify potential improvements in water savings and crop yields and, subsequently, provide future outlook of water and land demand for crop production in data-scarce regions. Primary datasets required to carry out the analysis include historical and forecasted population time series, crop statistics, crop parameters, and multiple remote sensing datasets. Population time series and national crop statistics required to assess production and consumption patterns as well as to construct future scenarios are available for almost all countries and territories in the globe (FAOSTAT, 2023; United Nations, 2023b). Ideally, crop parameters should be specific to the location and varieties under study. If exact values for parameters are not available in the study region, the use of average values from other regions with similarities to the study region may be justified. A plethora of remote sensing products to estimate crop yield and water productivity are available, with varying spatial and temporal resolutions, time and geographical coverages, and performance quality (Blatchford et al., 2019). However, the minimum requirement to conduct such crop-specific exercise is the availability of a crop type layer that distinguishes between crop types and seasons. This layer is often unavailable since crop type information has been traditionally obtained from expensive and time-demanding field surveys to conduct. Even when a crop layer is available, it is likely to be limited to space and time, hindering its use in multi-season assessments. The WaPOR's crop type layer used herein is also available for a number of irrigated areas in other countries, e.g., Sudan, Lebanon, Ethiopia, Mali, Rwanda, Senegal, and Sri Lanka, covering the period from 2009 to present. An alternative to the ready-to-use crop type layers by WaPOR or similar initiatives, researchers can use remote sensing techniques to self-produce crop type maps (Joshi et al., 2016; Kluger et al., 2021; Orynbaikyzy et al., 2019). The choice of specific remote sensing products required to conduct such exercise depends on the accessibility to the product, the purpose of the study, the spatial and temporal coverages, and the performance quality of the product over the specific study area. Should the product produce systematic over- or underestimates of certain parameters, we recommend adopting our approach of relying on the relative than the absolute values when conducting the analysis, i.e., estimating potential improvements in percentage as the ratio of the higher to average values in the area under investigation.

4.4.5. Limitations and future research

We attempted to collect representative values of crop parameters used in the analysis from literature (Table 4.2), of which some were not available from Egypt and were thus collected from other arid regions. However, crop parameters can vary between locations and varieties, and it is recommended to use locally calibrated values when utilizing the methodological approach of this study in future research and application. Although we deemed Zankalon as a suitable and representative case to detect performance variation and potential improvements, it is important to acknowledge that this assumption may not fully align with the spatio-temporal heterogeneities on the ground across the country, and there could be variations beyond what our analysis captured. Our analysis focused on four major crops, however, it would be helpful to expand the analysis to include as many crops as possible. To do so, there is a need for operational and temporally dynamic crop type maps covering partly or fully the cropland extent. Although not included in our analysis, climate change will impact the demand for resources and supply capacity in Egypt. Future assessments may include climate change impacts on crop water requirements, crop productivity, sea level rise, saltwater intrusion, and future Nile water availability and variability. Future assessments may also investigate scenario of crop substitution, dietary change, and adjusting trade portfolio.

4.5. Conclusion

In Egypt, approximately half of annually harvested areas and renewable freshwater are allocated for cultivating rice, maize, wheat, and berseem clover. Given the limited resource availability in the country, it is imperative to understand the potential improvements in the production of these crops and associated water and land requirements. We used the case study of Zankalon to explore the potential improvements of cultivating these major crops in Egypt. Given the scarcity of ground data in Egypt, our methodology relied on high-resolution datasets of WaPOR to benchmark performance indicators and quantify potential improvements in Zankalon, namely crop yield, water productivity, and transpiration fraction. Subsequently we used the potential improvements and national statistics to develop scenarios of future demand for water and land to sustain production of these crops from 2021 through 2050 in Egypt.

WaPOR demonstrated reasonable quality in estimating performance indicators for winter crops in Zankalon. However, a significant underestimation of yield and water productivity for summer crops was observed. Thus, we do not recommend relying on WaPOR for estimating absolute values these indicators for summer crops in irrigated arid regions similar to Zankalon.

Our findings revealed the anticipated challenge for Egypt to secure sufficient resources, particularly water, to sustain production of the four crops by 2050. Maize and wheat would be the most demanding crops for water and land resources, followed by rice and berseem. Although the findings suggest a relatively good production performance of these crops, they also show that there is room for improvement. In general, the implementation of interventions to improve production efficiency would result in more significant production improvements for rice and maize than for wheat and berseem.

We discussed potential interventions to improve productivity of these crops through appropriate crop management practices. The high demand for crops estimated herein is mainly driven by the rapid population growth and the high reliance on specific crops. Thus, it is essential to curb the continuous rise in crop demand, either by bending the population growth curve or by promoting change in dietary patterns. Further interventions such as improving field and conveyance efficiencies, crop substitution, reduction of food losses, intensifying use of non-conventional water resources, and revisiting water allocation and trade strategies, can help Egypt bridging the gap between its food demand and supply capacity.

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5. The Eastern Nile countries (Egypt, Sudan, and Ethiopia)

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Abstract

Securing agricultural commodities for a growing population requires a paradigm shift in agricultural thinking. An appropriate agricultural development pathway should be determined, which may include larger land extensions and water consumption or more intensive use of smaller extensions and optimized water use. This study addresses this question in the Eastern Nile Basin countries (ENC), namely Egypt, Sudan, and Ethiopia, where such research is scarce. We utilized open-source datasets, based on relevant remote sensing products and agricultural statistics (harvested area, production, yield, and water footprint [WFP]), to understand the spatio-temporal variability of cropland performance. The study proposes a scenario-based approach that evaluates four development pathways towards sufficient crop production by 2050 in the ENC. While the extensification pathway suggests a continuation of the business-as-usual, i.e., same current WFP and average yield values (horizontal scenario), three intensification pathways assume that increased efficiency can improve WFP and yield values (vertical scenarios). Results show that substantial amounts of water and land could be saved by 2050 by following the vertical development pathways. Nonetheless, the three countries, especially Egypt, are expected to face enormous challenges to satisfy their future demand for the main crops by 2050. Our research provides key messages to promote cooperation and benefit-sharing between the three countries by following a regional benefit-sharing approach to the challenge. The findings of the current study have deep implications on sustainable natural resources development and water and food security in such a vital and conflicted region.

5.1. Introduction

Future population growth is expected to increase pressure on agricultural systems to produce more commodities. This anticipated increase in food demand would significantly escalate the use of natural resources, especially water and land. Climate and its variability pose additional challenges to agricultural systems. Due to factors including rising temperatures, erratic precipitation, and increasing frequency of extreme events, such as droughts and floods, many regions worldwide will likely experience depressed yields (Tubiello and Fischer, 2007), possibly turning agriculture into a riskier endeavor and consequently endangering food security. Thus, a paradigm shift is needed to build water resilience in agriculture (Rockström et al., 2009) and produce more from the same area of cultivated land (Cosgrove and Loucks, 2015; Duncan et al., 2015).

While many countries in Oceania, Western and Northern Europe, North and South America, and South-East Asia noticeably improved agricultural productivity in recent decades (Licker et al., 2010; Pradhan et al., 2015), poor performance persists in many other regions, notably sub-Saharan Africa (van Ittersum et al., 2016). Examples of poor agricultural performance have been observed in Sudan (Al Zayed et al., 2015), Southern Africa (Mango et al., 2017; Rusere et al., 2019), Pakistan (Muzammil et al., 2020), China (Zhang et al., 2017), and Brazil (Rada et al., 2019). The low efficiency of agricultural systems in many regions indicates the enormous potential for increased crop production from the same cultivated lands. Therefore, improved efficiency, combined with minimized natural resource use, may significantly contribute to solving the expected future global food crisis (Foley et al., 2011). To this end, spatio-temporal information regarding the potential for crop yield improvement and water-saving is fundamental. Such knowledge is not always available, especially in developing countries. Therefore, assessments based on public-domain data, which involve spatial and temporal dimensions and provide future outlooks, can play an essential role in addressing the current challenge and contribute crucial knowledge needed to investigate the optimal sustainable development pathways.

Recent developments in satellites and remote sensing techniques have made it possible to more accurately quantify precipitation (P), net primary productivity (NPP), and actual evapotranspiration (AET) with an adequate spatial and temporal resolution. As a result, we can comprehensively investigate the water use efficiency (WUE) and crop water productivity (CWP), which are informative indicators for assessing agricultural land performance. Despite this considerable advancement in the field, creating useful knowledge from this continuously accumulated big data represents (i) an opportunity as it offers exceptional spatial and temporal coverage and (ii) a challenge due to the uncertainty involved in such satellite-based data. Nevertheless, converting this big data into useful knowledge is vital (Sudmanns et al., 2019).

Like many regions around the world, the Eastern Nile Basin countries (hereafter, ENC), i.e., Egypt, Sudan, and Ethiopia, plan to expand their irrigated agriculture projects to respond to the increasing demand for food production (Awulachew et al., 2007; Blackmore and Whittington, 2008; Hamouda et al., 2009), which will require additional water and land resources. Among the planned developments are large water infrastructure projects for both the development of hydropower generation and to meet the water demand of future irrigated areas. However, such unilateral plans could aggravate the hydro-political tension among the ENC. In addition, the region is expected to experience vulnerabilities in the future due to climate change (Baldassarre et al., 2011; Siam and Eltahir, 2017), which could potentially jeopardize its agricultural systems. These issues position the ENC countries to require all future developments to (i) fulfill the demand of a growing population, (ii) maintain the transboundary peace, and (iii) demonstrate resilience to expected climatic variabilities. Achieving such complex development requires a proper quantification of the available resources as well as consumption patterns and future demands.

Numerous studies have been conducted on the ENC mainly—but not exclusively—to (i) assess the potential for regional cooperation and conflict management (e.g., Al-Saidi and Hefny, 2018; Amer et al., 2005; Jeuland et al., 2017; Mason et al., 2009; Motlagh et al., 2017; Tawfik, 2019), (ii) analyze treaties and legal frameworks (e.g., Ferede and Abebe, 2014; Salman, 2013), and (iii) explore cooperative dam operation and streamflow scenarios and perform hydrological modeling for the basin (e.g., Arjoon et al., 2014; Basheer et al., 2018; Bastiaanssen et al., 2014; Digna et al., 2017; Goor et al., 2010; Mengistu and Sorteberg, 2012; Wheeler et al., 2016, 2018; Zhang Ying et al., 2015). Over the last decade, only few studies have investigated future scenarios of expanding irrigation schemes (Awulachew et al., 2012), improving irrigation efficiency (Multsch et al., 2017), changing contribution of green and blue water for food production (Sulser et al., 2010), and maximizing hydro-economic benefits (Siderius et al., 2016) in the entire Nile Basin. To the best of our knowledge, no studies have either examined the spatio-temporal variation of WUE and CWP throughout the ENC or quantitatively assessed future development scenarios regarding the required water and land resources towards sufficient crop production in the three riparian countries.

The overarching aim of this research is to determine the agricultural development pathway that optimizes water conservation, land savings, and crop production. The ultimate goals are to (i) understand the ENC spatio-temporal variation in cropland area, P, NPP, AET, WUE, and CWP; (ii) assess the potential for crop production and water and land savings; (iii) provide a future outlook on the required water and land resources of different agricultural development pathways by 2050. The results provide a holistic overview of the anticipated deficit in water and/or land resources in each scenario and, subsequently, recommendations for achieving a more sustainable agricultural development pathway in the ENC. This research contributes directly to our understanding of the potential to achieve several Sustainable Development Goals (SDGs) (United Nations, 2015) in the ENC, specifically SDG 2.3 (doubling agricultural productivity), SDG 6.4 (increasing water use efficiency), and SDG 12.2 (sustainable management and efficient use of natural resources).

The current research's novel contribution is in providing quantitative water and land use estimates for the development pathways. Despite the intuitive understanding that intensification in agriculture is more feasible than extensification, no previous study has characterized this quantitatively on the ENC scale. Our study also demonstrates novel versatility in method and data utilization. Using remote sensing to understand the spatio-temporal variation in climatic variables, vegetation productivity, WUE, and CWP provides unprecedented spatial and temporal coverage that is not possible via *in-situ* measurements. This coverage could advance our understanding of the prospects for improvements and guide the selection of the most appropriate development scenario.

5.2. Materials and methods

5.2.1. Study area

The Eastern Nile Basin has an area of 1.7 x 10^6 km^2 and extends over five countries: Egypt, Sudan, Ethiopia, Eritrea, and South Sudan (Fig. 5.1). We limit the scope of the current analysis to Egypt, Sudan, and Ethiopia, as water withdrawal in the agricultural sector in South Sudan and Eritrea is negligible compared to that in the other three countries. Agriculture is not only the primary source for livelihood and food production in the three riparian countries but also the primary water user. Specifically, water withdrawals for agriculture account for nearly 79%, 96%, and 92% of the total water withdrawals in Egypt, Sudan, and Ethiopia, respectively (AQUASTAT, 2016). While the agricultural system solely uses irrigation in Egypt, both irrigated and rainfed agriculture are practiced in Sudan and Ethiopia. Cereal crops, such as wheat, maize, sorghum, millet, and teff, dominate the cultivated cropland and provide the major percentage of daily calories for the ENC people.

Water scarcity is a common issue in the ENC. Based on the total renewable blue water resources (AQUASTAT, 2016) as well as the current and forecasted population (medium-fertility variant) of the three countries (United Nations, 2023b), the per capita share of blue water resources is currently characterized as "stressed" in Sudan (≈ 880 m^3 cap^{-1}) and Ethiopia (≈ 1100 m^3 cap^{-1}) and as "scarce" in Egypt (≈ 570 m^3 cap^{-1}), with predicted values of 465, 595, and 360 m^3, respectively, per capita by 2050, implying absolute scarcity.

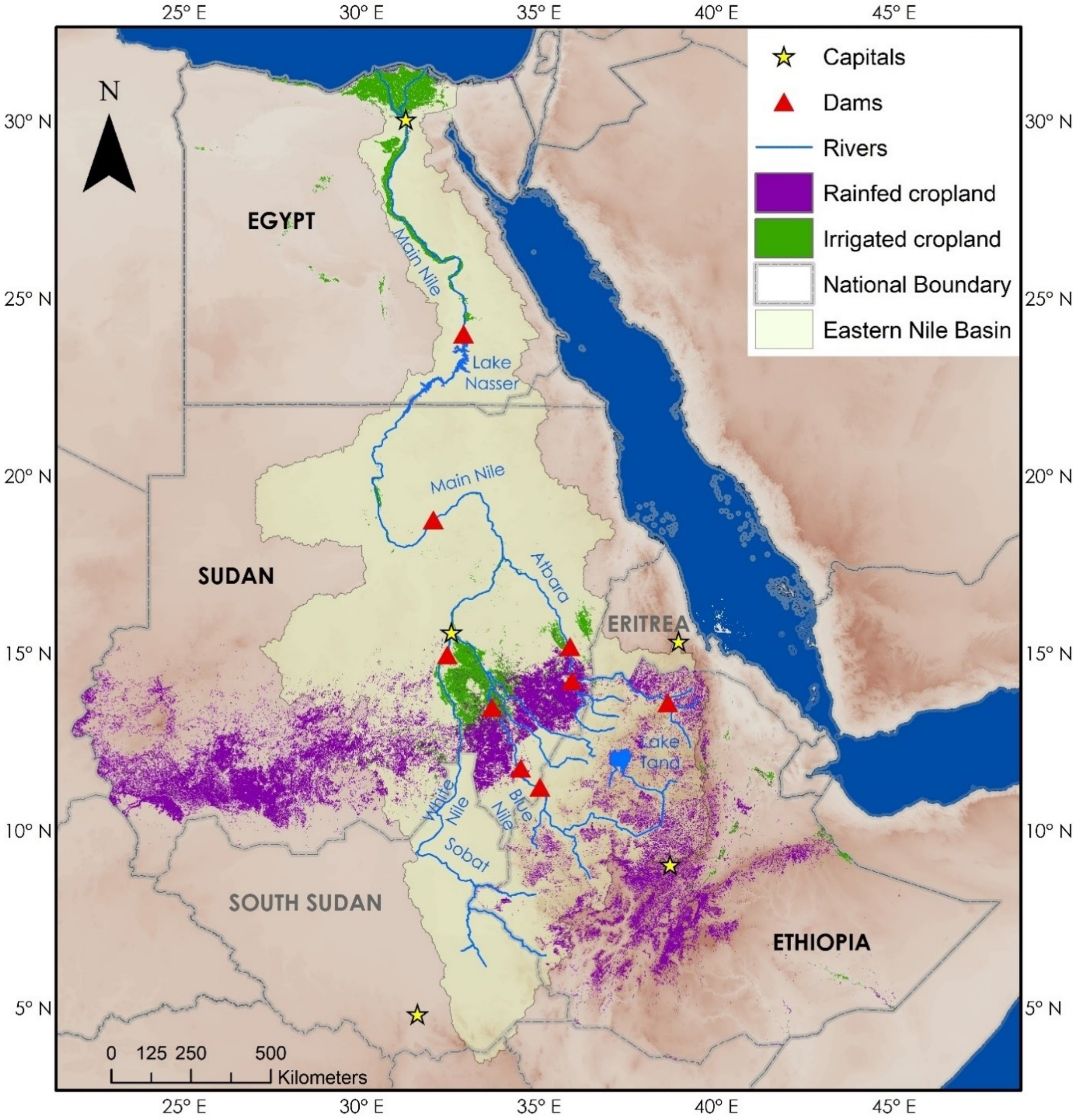

Fig. 5.1. Location map of the Eastern Nile Basin with main tributaries and dams in Ethiopia, Sudan, and Egypt. The spatial distribution of rainfed and irrigated croplands in three countries is derived from the ESA-CCI land cover product.

5.2.2. Definition of agricultural terms

5.2.2.1. Water use efficiency (WUE) and crop water productivity (CWP)

In its broadest sense, WUE reflects multiple ecosystem functions and is defined as the ratio of plant carbon assimilation to water consumption (Fischer and Turner, 1978; Rosenberg et al., 1983). Scholars adapted the WUE concept to develop the CWP concept, defined as the ratio of net benefits produced, such as crop yield or economic returns, to the required water quantity to produce those benefits (Molden et al., 2010, 2003). Depending on the nature of the research, WUE components can be defined in several ways (Fernández et al., 2020). In this study, we adopt the CWP and WUE concepts. While the former is estimated through grain yield and AET, in the latter, plant carbon assimilation (biomass) is quantified by the NPP, and water consumption is represented by AET.

5.2.2.2. Water footprint (WFP) and crop yield gap

The concepts of WFP and crop yield gap are essential indicators for understanding the water-food nexus. Both concepts have received considerable attention in recent decades (Hoekstra et al., 2011; Lobell et al., 2009). WFP is defined as “the total volume of freshwater that is used directly or indirectly to produce the product” (Hoekstra et al., 2011; p.46). The WFP of a product can contain green (rainwater stored in the soil), blue (surface and groundwater), and gray (freshwater to assimilate the load of pollutants) waters. Therefore, it can act as a good indicator of water usage in agricultural production systems. WFP differs widely in spatial and temporal domains. According to Mekonnen and Hoekstra (2011), WFP varies among crops: the global average WFP of cereal crops is approximately 1,644 m^3 ton^{-1}, while for coffee, the WFP can reach up to 24,700 m^3 ton^{-1}.

The crop yield gap describes the difference between what growers are potentially able to produce for a given crop (potential yield) and what is actually obtained (actual/attainable yield) (Mueller et al., 2012). The magnitude of crop yield gap varies considerably around the world and under different agricultural systems. This phenomenon is widespread in all crops and all regions of Africa (Tittonell and Giller, 2013). Identifying the causes of the yield gap is essential to close this gap (Lobell et al., 2009). Generally, fertilizer use, irrigation, and climate are the most influential factors on yield, and managing water resources and nutrients can potentially help to bridge this gap (Mueller et al., 2012).

5.2.3. Data

5.2.3.1. Remote sensing datasets

To achieve the study objectives in such a data-scarce region, we utilized several remote sensing datasets. These datasets were used to explore the spatio-temporal variability of cropland performance by analyzing products for land cover, P, NPP, and AET, and subsequently, producing a time series and mapping the WUE throughout the ENC. Using remote sensing datasets adds a spatial component to the analysis of these indicators, which is not only useful for such assessment across the countries but also facilitates comparison within each country. Specific products were selected based on the availability of extensive spatial and temporal coverages and accessibility through public-domain sources (Table 5.1). The selected datasets were downloaded for the available common period of all studied indicators (2003–2018) and were processed using ArcGIS 10.7 software (ESRI, 2019).

Table 5.1. Description of remote sensing datasets used in the current research (P = Precipitation, AET = Actual evapotranspiration, NPP = Net primary productivity).

Dataset	Product	Spatial and temporal resolution	Download website
Land cover	ESA-CCI	300 m; Annual	https://www.esa-landcover-cci.org/
Land cover	MCD12Q1	500 m; Annual	https://lpdaac.usgs.gov/products/mcd12q1v006/
Land cover	WaPOR	250 m; Annual	https://wapor.apps.fao.org/home/WAPOR_2/1
P	CHIRPS	5 km; Annual	https://www.chc.ucsb.edu/data/chirps
AET	SSEBop	1 km; Annual	https://earlywarning.usgs.gov/fews
NPP	MOD17A3	500 m; Annual	https://lpdaac.usgs.gov/products/mod17a3hv006/

5.2.3.2. Land cover dataset

A land cover dataset was needed to delineate the cropland before analyzing the indicators listed in Section 5.2.3.1. We analyzed three land cover datasets: (1) the European Space Agency Climate Change Initiative with 300 m spatial resolution (ESA-CCI; ESA, 2017), (2) the Terra and Aqua combined MODIS Land Cover dataset version 006 (1000 m) (MCD12Q1; Friedl et al., 2010), and (3) the FAO portal to monitor WAter Productivity through Open-access of Remotely sensed derived data with a spatial resolution of 250 m (WaPORv2.1; FAO, 2018). Detailed information about different land cover classes of each product and their corresponding ID numbers and descriptions can be found in the corresponding data sources. The selected classes from each product to delineate cropland in each country are presented in Table 5.2. After extracting the cropland areas from the three products (2009–2018), we compared them temporally with available data on cropland areas from FAOSTAT (FAOSTAT, 2018) and national statistics agencies in each country: (1) the Central Agency for Public Mobilization And Statistics (CAPMAS) in Egypt (CAPMAS, 2020), (2) the Central Bureau of Statistics (CBS) in Sudan (CBS, 2020), and (3) the Central Statistical Agency (CSA) of Ethiopia (CSA, 2020). Spatially, our comparison was guided by the Global Food Security Analysis-Support Data (GFSAD) product with a 30 m resolution only available for the year 2015 (https://www.croplands.org/app/map). Based on the results of these comparisons, one land cover product was selected, and land cover maps were produced and used in the analysis of P, NPP, AET, and WUE. For consistency, all products were resampled to a unified spatial resolution of the best-performing land cover product, using the “nearest neighbor" method to minimize the loss of any information.

Table 5.2. The selected land cover classes from each product to represent cropland in the ENC.

Country	Product					
	ID	WaPOR	ID	ESA-CCI	ID	MCD12Q1
Egypt	41	Cropland, rainfed	10	Cropland, rainfed	12	Croplands
	42	Cropland, irrigated	20	Cropland, irrigated	14	Cropland/natural vegetation
			30	Cropland/natural vegetation[a]	10	Grasslands[a]
Sudan & Ethiopia	41	Cropland, rainfed	10	Cropland, rainfed	12	Croplands
	42	Cropland, irrigated	20	Cropland, irrigated	14	Cropland/natural vegetation

[a] According to Ayyad et al. (2019), three vegetation classes from MCD12Q1 are selected to detect the full extent of cropland in Egypt. Similarly, we selected three classes from ESA-CCI that cover the same extent.

5.2.3.3. Precipitation

Since our study investigates both irrigated and rainfed croplands, a proper quantification of precipitation over the two types is required. We used the Climate Hazards group InfraRed Precipitation with Station data (CHIRPSv2.0) global annual product with 5 km spatial resolution. The product is developed by the United States Geological Survey (USGS) and the Climate Hazards Group of the University of California to support the Famine Early Warning Systems Network (FEWS NET) (Funk et al., 2015). CHIRPS 2.0 is a blended dataset that combines information from remote sensing and ground observations from several public and private sources. This product was evaluated in several studies within the Nile Basin and showed excellent performance in estimating precipitation (Ayehu et al., 2018; Dinku et al., 2018; Gebremicael et al., 2017; Nashwan et al., 2019). The annual precipitation maps were clipped to the spatial extent of cropland and time series were produced for each country (2003–2018).

5.2.3.4. Net primary productivity

The study employed the NPP annual product provided by Terra MODIS (MOD17A3) version 006 (Zhao et al., 2005). The MOD17A3 has been utilized in several regions in Africa (Abdi et al., 2014; Khalifa et al., 2018). The product offers global coverage at a spatial resolution of 500 m. We created annual NPP maps and time series (in g carbon m^{-2}) from 2003 to 2018 for each country.

5.2.3.5. Actual evapotranspiration

We used the AET product acquired from the FEWS NET. This dataset was developed by the USGS Earth Resources Observation and Science (EROS) Center and derived from the Operational Simplified Surface Energy Balance algorithm (SSEBop), initially developed by Senay et al. (2013). Data of version 4 of this product are available at a spatial resolution of 1 km and in 10-day, monthly, and annual timesteps. The annual product was used herein to quantify the total annual agricultural water consumption. The performance of the SSEBop product was recently evaluated and demonstrated high performance in estimating AET over Egypt (Ayyad et al., 2019) and Africa (Weerasinghe et al., 2020). We produced annual AET maps and time series (2003–2018) for the three countries.

5.2.3.6. Datasets used in scenario development

To build future scenarios, we need to understand and calculate the trends in production and consumption patterns. Thus, historical data of population estimates and crop statistics, i.e., cultivated area, yield, and production quantities, are needed. For each country, we used the historical and forecasted time series for the total population (low, medium, and high-fertility variants) from 1993 to 2050 (United Nations, 2023b). The crop statistics were collected from the FAOSTAT database between 1993 and 2018 (FAOSTAT, 2018). FAOSTAT collects data on crop production and harvested area through devoted annual questionnaires to official national sources. However, due to the absence of some data in some years, official data are sometimes supplemented with data from unofficial sources and information supplied by other national or international agencies. The majority of the data we obtained from FAOSTAT are described as official data, except for a few years—particularly in Sudan—reported as unofficial figures. To ensure the utilized numbers were of reasonable quality, we compared the obtained crop statistics from FAOSTAT to their counterparts from each country's national central agency, i.e., CAPMAS in Egypt, CBS in Sudan, and CSA in Ethiopia. Crop statistics of CAPMAS (2004–2017) were only available for wheat, rice, cotton, and sugarcane and showed nearly identical numbers to those provided by FAOSTAT. Likewise, FAOSTAT crop statistics were similar to those of CSA in Ethiopia (2001–2012). When comparing them at the annual scale, the CBS data on crop statistics in Sudan showed some inconsistencies, in some years, with FAOSTAT data. However, the multi-year average values from the two datasets were found to agree. The period (1993–2018) was selected because Eritrea became independent from Ethiopia in 1993. For the period 1993–2011, FAOSTAT provides data for former Sudan (Sudan + South Sudan), which were used to represent Sudan solely in the present study.

We selected 25, 14, and 24 crop types in Egypt, Sudan, and Ethiopia, representing 90%, 97%, and 96% of all cropping areas in the three countries, respectively. Based on our analyses of the datasets obtained from FAOSTAT, the selected cereal crops dominate the cropping areas with 59%, 67%, and 67% in Egypt, Sudan, and Ethiopia, respectively. In Egypt, the average harvested areas (1993–2018) of selected pulses, vegetables, fiber crops, oil crops, roots and tubers, fruits, and sugar crops represent 2.3%, 7%, 4.7%, 2.1%, 2.4%, 7.5%, and 4.7% of all cropped area in the country. Similarly, the selected pulses, vegetables, fiber crops, oil crops, roots and tubers, and sugar crops form 1.8%, 0.3%, 1.1%, 25.3%, 0.5%, and 0.5% of the cropped area in Sudan. In Ethiopia, the studied pulses, vegetables, fiber crops, oil crops, roots and tubers, coffee, and pimento constitute 10%, 1.4%, 2.7%, 4.8%, 5.8%, 3.1%, 0.6% of the cropped area. A detailed list of the selected crops in each country is in Appendix B, Table B1. Time series (1993–2018) of crop statistics, i.e., production, harvested area, and yield, were created for all selected crops.

The average WFP values (1996–2005) for each crop in each country were collected (Mekonnen and Hoekstra, 2011a). It should be noted that WFP values used in the current study are the sum of green, blue, and grey water footprints to account for the direct and indirect water consumption for each selected crop (Hoekstra et al., 2011). Finally, the renewable water resources and areas of currently cultivated land in the three countries were acquired (AQUASTAT, 2016; FAOSTAT, 2018).

5.2.4. Methods

5.2.4.1. Calculation of WUE and CWP

The WUE was calculated for each country as the ratio of NPP to AET: grams of carbon per millimeter of water evapo-transpired per square meter of cropland (in g C mm^{-1}). Time series for the period from 2003 to 2018 was created by dividing the annual average values of NPP by their corresponding AET values. Next, we plotted the WUE spatial distribution by dividing the two datasets (NPP/AET), using the “raster calculator” function in ArcGIS. We calculated the CWP by dividing the total yield values of all primary crops obtained from FAOSTAT by their corresponding observed AET values (2003–2018) for each country (in kg m^{-3}). This approach provides important insights into the performance of croplands within and across the ENC.

5.2.4.2. Statistical analyses

The Mann-Kendall statistical test was performed to detect trends in P, NPP, AET, CWP, and WUE in the three countries. The null hypothesis (H_0) of the Mann-Kendall test assumes no trend in the time series under evaluation. For this analysis, GSI Mann-Kendall Toolkit v. 1.0 (Connor et al., 2012) was used. This tool generates seven possible trends using the Mann-Kendall statistic (S), confidence level (CL), and coefficient of variation (CV). These possible trends are (i) increasing ($S > 0$, $CL > 95\%$), (ii) probably increasing ($S > 0$; $95\% \geq CL \geq 90\%$), (iii) no trend ($S > 0$; $CL < 90\%$), (iv) no trend ($S \leq 0$; $CL < 90\%$ and $CV \geq 1$), (v) stable ($S \leq 0$; $CL < 90\%$ and $CV < 1$), (vi) probably decreasing ($S < 0$; $95\% \geq CL \geq 90\%$), and (vii) decreasing ($S < 0$; $CL > 95\%$).

To explore the inter-annual variability of P, NPP, AET, CWP, and WUE, we calculated the CV by dividing the standard deviations by the mean annual values. We produced CV maps for AET and WUE over the cropland in each country (2003–2018). Maps of standard deviation and mean were produced using the "cell statistics" function for each dataset and were subsequently divided using the "raster calculator" function.

5.2.4.3. Scenario development

The present study developed a framework to forecast future crop demands and, thereafter, proposed development scenarios for the ENC (Fig. 5.2). Although FAOSTAT provides data on each crop's per capita food supply quantity, we calculated the average supply value per capita (kg/capita/year) from 1993 to 2018 as the ratio of the annual production quantity to population. We chose this method for two reasons: (1) to avoid involving import and export calculations, i.e., any import or export ratios are assumed constant, and (2) for some of the selected crops (e.g., maize in Egypt), large portions of the production quantities are used as livestock and poultry feed rather than for direct human consumption. The calculated per capita average supply was considered to remain unaltered through 2050. To estimate future demands for all selected crops by 2050, each crop's per capita average supply quantity was multiplied by the population forecasts (low, medium, and high-fertility variants) for each year from 2019 to 2050, assuming that no change in population dietary patterns would occur. We used these three variants to produce a range of possible values for our estimates (minimum, average, and maximum) since single values might not be useful to policymakers. Furthermore, because our scenarios aim to provide a future outlook, reporting ranges would propagate potential uncertainties in the results and make them more realistic.

Based on the calculated future demands of selected crops until 2050, the study followed a scenario-based approach that evaluates four different development scenarios in each country. The scenarios include an extensification pathway (horizontal; clearing additional land for crop production) and three intensification pathways (vertical; producing more from the same cultivated area).

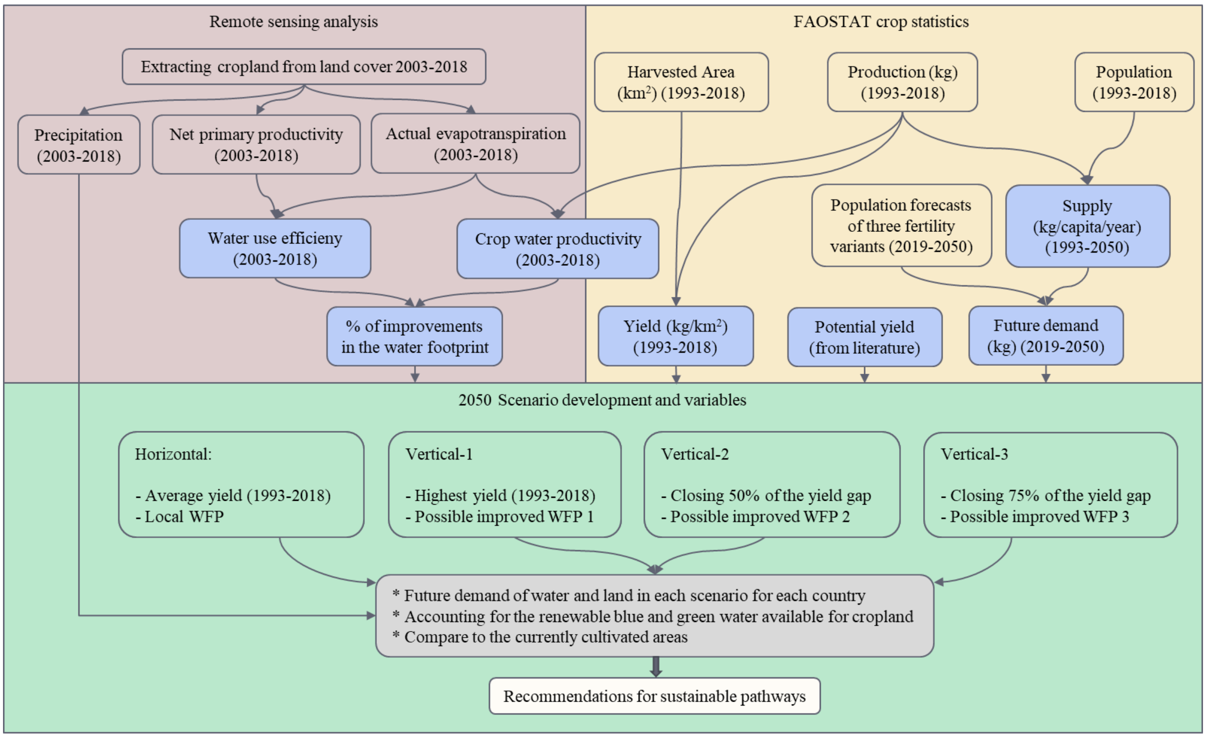

Fig. 5.2. The methodological framework of the current study.

5.2.4.4. Scenario variables

The extensification pathway (hereafter, horizontal scenario) represents the “business as usual” situation. This involves expanding the area of cultivated lands following the current field practices, i.e., implying no change in WFP and land productivity “yield”. In this scenario, average yield (1993–2018) and local WFP values are considered to remain unchanged until 2050. Alternatively, the three intensification pathways (hereafter, vertical scenarios), namely V-1, V-2, and V-3, assume improved WFP and yield values for each crop. One bottleneck in such a large-scale assessment is identifying thresholds of improvements in WFP in vertical scenarios since information on WFP is only available as single average values (1996–2005). Given the strong variability in farming practices within and across the three countries, relevant studies assume normative values for potential improvements in water use efficiency (e.g., Multsch et al., 2017). In this study, we used the statistical analysis of CWP and WUE (Section 5.2.4.2) to identify the likelihood of improvements in WFP, i.e., CV values as proxies for potential improvements in WFP. Consequently, we assumed three percentages for potential improvements in the WFP values for each scenario in each country.

Regarding the yield, we selected the highest attained yield values recorded for each crop (1993–2018) to represent yield values in V-1, assuming that the highest attained yield would be achieved again. Next, we extracted potential yield values of the dominant crops (i.e., cereals) reported in the literature, derived either through field experiments, crop modeling, or other statistical methods (Appendix B, Table B2). We found high variability between potential yield values in literature and the highest attained yield values from FAOSTAT. Potential yield values were averaged for each crop and, consequently, crop yield gaps were calculated as the difference between attainable and potential yield values. Yield gaps (%) were then calculated as acreage-share weighted average percentages of the selected cereals. These percentages were assumed for all other crops in each country since we could not retrieve potential yield values for all selected crops. Although experimental and simulated yields do not reflect the real farming conditions, they can be used to identify yield thresholds (van Ittersum et al., 2013). Thus, we selected two percentiles (50% and 75%) of the yield gap and assumed these gaps to be closed in V-2 and V-3, respectively.

Multiple interrelating factors determine yield in the region, e.g., climate stability, field and soil management, crop varieties, the existence of appropriate infrastructure and technological packages, enforced policies, the use of fertilizer and pesticide as well as the socio-economic status of farmers and other factors (Elagib et al., 2019; Karimi et al., 2012; Khalifa et al., 2020; Thornton et al., 2018). Given the large variation in physical parameters, socio-economic statuses, and field practices within and across the ENC, we could not incorporate these factors into our large-scale assessment. Instead, we deal with the yield values resulting from existing or modeled yield-determining factors. For the required intervention to improve crop yield in the region, the reader is referred to the above-listed studies and the literature used to extract potential yield values (Appendix B, Table B2).

For each scenario, we calculated the land area required by 2050 by dividing each crop's future demand by their corresponding yield values. The future demand of each crop was multiplied by their respective WFP to calculate the water quantities needed by 2050. The calculated demands of water and land for all crops were compared to the renewable water resources and the area of currently cultivated land in the respective countries to detect the consequences of each development pathway by 2050.

5.3. Results and discussion

5.3.1. Land cover

In Egypt, the spatial distribution of cropland was consistent among the three products and GFSAD. Temporally, the average cropland areas (2009–2016) extracted from MCD12Q1, WaPOR, and ESA-CCI compare very well with their counterparts from FAOSTAT and CAPMAS, although ESA-CCI was slightly better in capturing cropland (Table 5.3). In Ethiopia, the average cropland areas (2009–2012) reported by FAOSTAT and CSA were higher than the extracted area from ESA-CCI, lower than MCD12Q1, and almost half of that extracted from WaPOR, demonstrating the latter's overestimation of cropland area in the country (Table 5.3). Spatially, MCD12Q1 showed intensive cropland in the northwestern region of Ethiopia (bordering Sudan), which conflicts with the cropland distribution provided by GFSAD, ESA-CCI, and WaPOR. Delineating cropland in Sudan seemed to be more challenging. FAOSTAT and CBS reported an average cropland area of 200,000 km^2. This value is lower than cropland area extracted from ESA-CCI, higher than WaPOR, and much higher than MCD12Q1 (Table 5.3). By comparing the spatial distribution of cropland from GFSAD with the three products, we concluded that the ESA-CCI product captured rainfed cropland areas not captured by MCD12Q1 and WaPOR. As a result, we considered the ESA-CCI to be a more reliable product for extracting cropland areas throughout the ENC. Similar results regarding the ESA-CCI high spatial correspondence in capturing cropland in Sudan and Ethiopia were reported by Tsendbazar et al. (2015).

Table 5.3. Summary of the results of cropland area, multi-year average of precipitation (P), actual evapotranspiration (AET), net primary productivity (NPP), water use efficiency (WUE), and crop water productivity (CWP), along with respective coefficient of variation (CV).

Cropland area	**Egypt**			**Ethiopia**			**Sudan**		
	km^2			km^2			km^2		
MCD12Q1	35,800			164,300			73,000		
WaPOR	40,800			277,400			183,000		
ESA-CCI	36,500			130,500			249,000		
FAOSTAT	37,000			158,700			200,000		
CAPMAS	37,400			-			-		
CSA	-			135,700			-		
CBS	-			-			200,000		
Other parameters	**Egypt**			**Ethiopia**			**Sudan**		
	mm	km^3	CV (%)	mm	km^3	CV (%)	mm	km^3	CV (%)
P	49	1.8	24.2	1114	145	6.5	480	95	12.3
AET	873	32	3	630	82	6	460	91	10
NPP	g C m^{-2}		CV (%)	g C m^{-2}		CV (%)	g C m^{-2}		CV (%)
	474		5.6	823		3.2	300		32.8
WUE	g C mm^{-1}		CV (%)	g C mm^{-1}		CV (%)	g C mm^{-1}		CV (%)
	0.55		4.4	1.31		4.4	0.18		29.5
CWP	kg m^{-3}		CV (%)	kg m^{-3}		CV (%)	kg m^{-3}		CV (%)
	2.54		10.3	0.41		25.5	0.23		13.2

The spatial distribution of croplands extracted from the ESA-CCI is presented in Fig. 5.1. Almost all cropland in Egypt were irrigated (98.1%) and concentrated in the Nile Delta and Valley. In contrast, the majority of extracted cropland in Ethiopia were rainfed (95.6%), stretching from the Rift Valley in the middle of the country to the country's northern, eastern, and western borders. Sudan cropland displayed irrigated (17%) and rainfed (83%) areas.

To understand how land cover change correlated with crop production, we calculated the Pearson's coefficient of determination (R^2) and significance level (P) between the annual cropland area extracted from ESA-CCI and the corresponding crop production quantities reported by FAOSTAT. We found a relatively high correlation between the land cover change and crop production in Egypt ($R^2 = 0.67$, $P = 0.0001$) and Ethiopia ($R^2 = 0.52$, $P = 0.0014$). However, an exceptionally low correlation ($R^2 = 0.007$, $P = 0.76$) was found between the two variables in Sudan. The low correlation in Sudan may be attributed to post-harvest losses (Schulten, 1982) and areas lost at harvest, i.e., when not all planted areas are harvested (Elagib et al., 2019).

5.3.2. Precipitation and net primary productivity

Precipitation over croplands in the ENC showed a decreasing gradient from south to north (Fig. 5.3a). Cropland in Ethiopia received the highest mean annual precipitation of 1114 mm, followed by Sudan 480 mm, and Egypt 49 mm (2003–2018). As the ESA-CCI product was found to overestimate the cropland area in Sudan by approximately 20% (Section 5.3.1), the precipitation volume over cropland in Sudan was reduced by 20% (Table 5.3).

The highest NPP values (2003–2018) were found in Ethiopia, with an average annual value of 823 g C m^{-2}, followed by Egypt (474 g C m^{-2}) and Sudan (72 g C m^{-2}). As shown in Fig. 5.3b, the northern areas of Egypt represented by the Nile Delta showed higher NPP values (300–1200 g C m^{-2}) than southern areas (< 300 g C m^{-2}). In Sudan, the spatial distribution of NPP demonstrated limited variability since the NPP of almost all croplands of the country was less than 300 g C m^{-2}. The highest NPP values in Ethiopia were found in the middle part of the country, with values from 600 to 1500 g C m^{-2}, decreasing northwards to around 300 g C m^{-2}.

Multiple factors determine the magnitude of NPP, most importantly, precipitation, humidity, altitude, temperature, and radiation (Li et al., 2016; Pan and Dong, 2018; Pan et al., 2015a, 2015b). In arid and semi-arid regions such as Sudan and Egypt, precipitation and temperature are likely the most influential NPP determinants (Li et al., 2016). Khalifa et al. (2018) found that NPP in Ethiopia and Sudan is directly influenced and positively correlated with precipitation. This correlation is reflected in the estimated NPP values in the two dry years (2009 and 2015), notably low in Sudan and Ethiopia (Fig. 5.3c and 5.3d). Additionally, croplands in Ethiopia may include natural vegetation with better canopy and vegetation types that are more efficient in assimilating atmospheric carbon dioxide than single crops that might appear in arid and semi-arid areas in Egypt and Sudan, which could also explain the high NPP in Ethiopia.

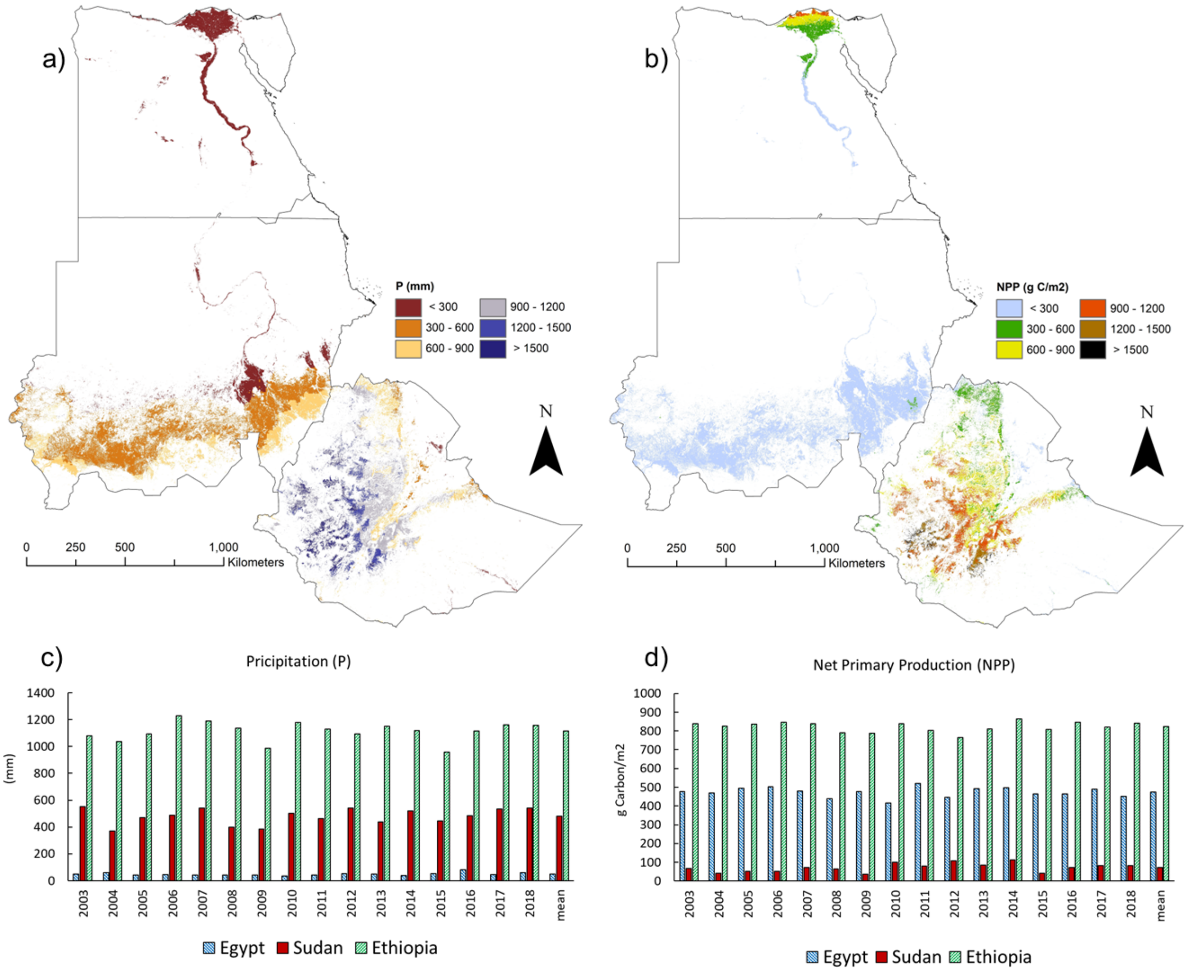

Fig. 5.3. Spatial variation of the multi-year average (2003–2018): (a) precipitation (P) and (b) net primary productivity (NPP), and time series of (c) P and (d) NPP.

5.3.3. Actual evapotranspiration

The SSEBop product analysis revealed high variations in the spatio-temporal distribution of AET over all croplands throughout the ENC (Fig. 5.4a and 5.4b). Egypt had the highest AET rates with an average annual value of 873 mm (32 km^3), followed by Ethiopia with 630 mm (82 km^3) and Sudan with 460 mm (91 km^3; similar to P estimation (Section 5.3.2), AET volume in Sudan was reduced by 20%) (Fig. 5.4b). Three major factors could explain the high variation in AET values among the ENC. The first is the type of agriculture (irrigated or rainfed) and the cropping intensity (the fraction of cropland that is harvested). Based on FAOSTAT data, we calculated the average cropping intensity (2003–2018) in the three countries. Egypt, with almost entirely irrigated areas (98.1%) had the highest cropping intensity of 145%, and Ethiopia (4.6% irrigated areas with 92% cropping intensity) showed higher AET values than Sudan (17% irrigated areas and 72% cropping intensity). The second factor is the spatial variability in the ENC climate conditions, ranging from a hyper-arid climate in Egypt to humid and wet-humid in the Ethiopian highlands, i.e., AET is higher with higher temperatures and lower humidity. Third, AET reflects the pattern of water availability. The inter-annual variability of AET can be explained by the calculation of CV, also known as the uniformity indicator of water use or water delivery (Karimi et al., 2019; Molden and Gates, 1990; Roerink et al., 1997).

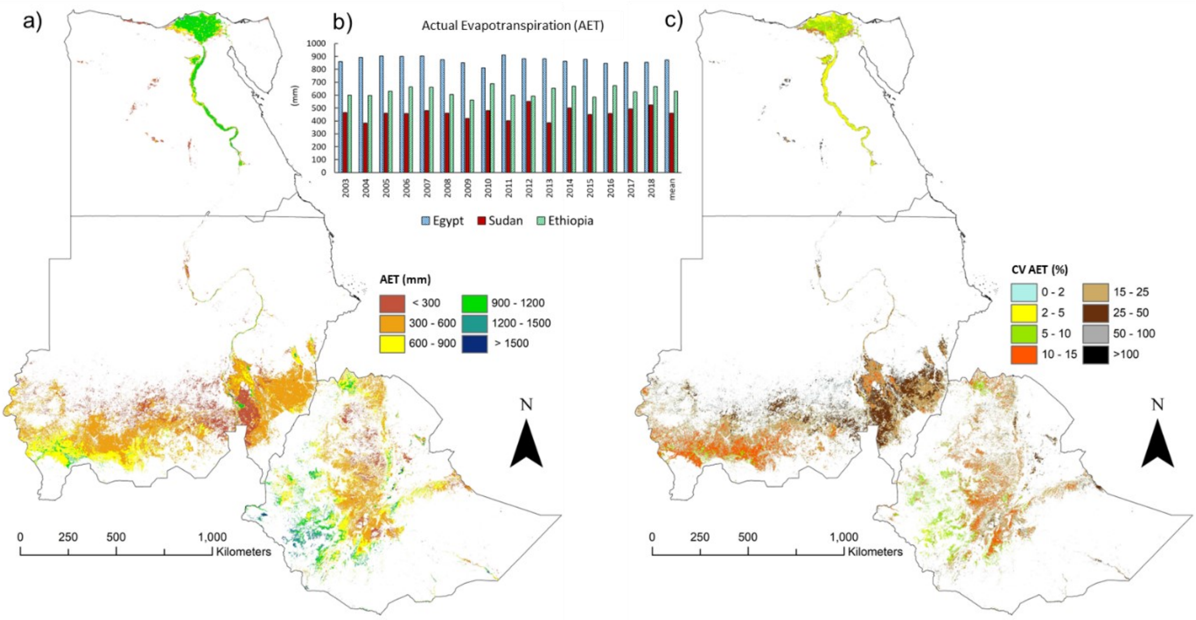

Fig. 5.4. (a) Spatial variation of the multi-year average (2003–2018) of actual evapotranspiration (AET). (b) AET time series. (c) Spatial distribution of the coefficient of variation (CV) (2003–2018).

According to Molden and Gates (1990), CV values of 0–10%, 10–25%, and > 25% imply good, fair, and poor uniformity in water use, respectively. Temporally, CV values associated with the 16-year average annual AET estimates are 3%, 10%, and 6% in Egypt, Sudan, and Ethiopia, respectively (Table 5.3), indicating a good uniformity in water use in all three countries. Spatially, the CV ranged widely throughout the ENC (Fig. 5.4c). Such variation could reflect the uniformity of water deliveries to croplands, i.e., water availability. For instance, CV values over the old cultivated areas in the middle of the Nile Delta and Valley showed a low spatial variation (CV ≈ 2–10%), indicating a high degree of water availability and good uniformity. In contrast, over the newly reclaimed lands at the fringe of the Delta and Valley where water deliveries are less available, CV values are higher (≈15–50%). The predominant CV values showed relatively high ranges in Sudan (≈10%–50%), indicating fair to poor uniformity. While in Ethiopia, except for the eastern part of the country (CV < 10%), the croplands demonstrated fair uniformity (CV ≈ 10%–25%).

5.3.4. Water use efficiency and crop water productivity

The WUE values widely varied among the ENC (Fig. 5.5a and 5.5b; Table 5.3), resulting from NPP and AET spatial and temporal variabilities. The entire irrigated cropland of Egypt exhibited an average WUE of 0.55 g C mm^{-1}. The country's cropland showed a high WUE (1.5

g C mm^{-1}) in the northern portion of the Nile Delta. Moving southwards, WUE declined to less than 0.05 g C mm^{-1}. In Sudan, almost all irrigated areas showed relatively low WUE values (< 0.05 g C mm^{-1}) compared to their counterparts in Egypt, implying a substantial potential for improvement. The rainfed cropland in Sudan along the southeastern and southwestern borders were also found to have higher WUE values (0.1 to 1.0 g C mm^{-1}) than irrigated cropland. While Sudan, among the three studied countries, had the lowest overall average WUE of 0.18 g C mm^{-1} over croplands, Ethiopia showed the highest average WUE value of up to 1.31 g C mm^{-1}. The WUE in Ethiopia demonstrated an increasing gradient from (0.1 to 0.5 g C mm^{-1}) along the northern borders to reach values higher than 3.0 g C mm^{-1} in the middle of the country, where rainfall and AET showed higher and lower rates, respectively.

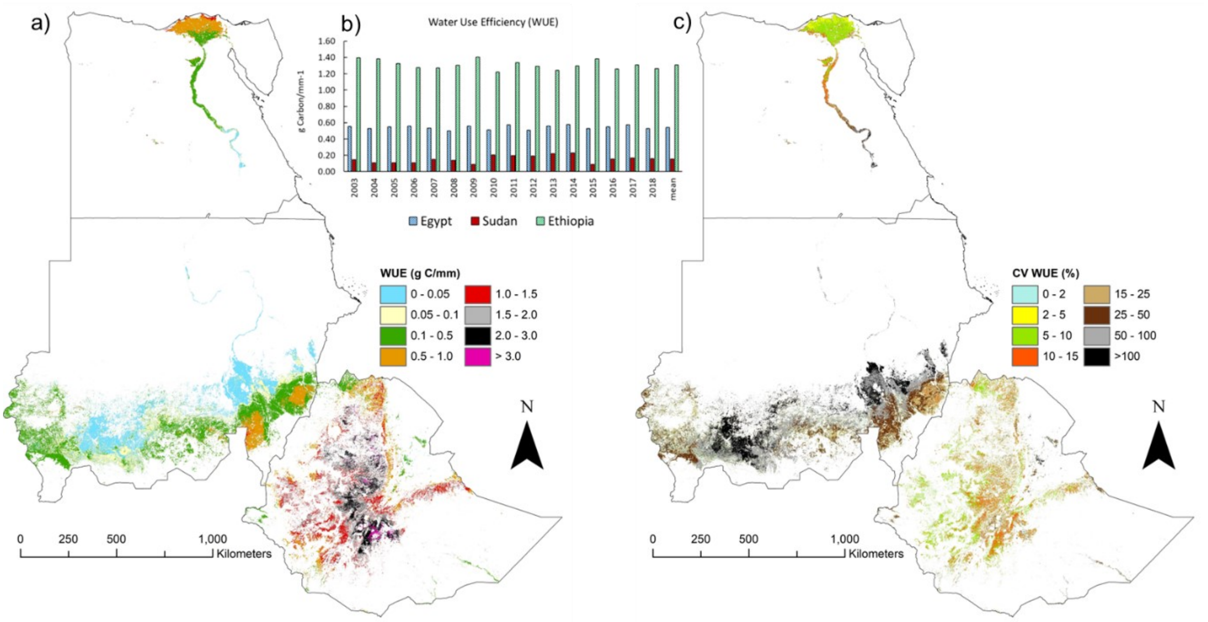

Fig. 5.5. (a) Spatial variation of the multi-year average (2003–2018) of water use efficiency (WUE). (b) WUE time series. (c) Spatial distribution of the coefficient of variation (CV) (2003–2018).

The WUE values for the three countries are comparable to previously reported values reported. The average WUE value for croplands Egypt is identical to the average WUE value (1895–2007) of croplands in the southern United States (0.54 g C mm^{-1}), as estimated by Tian et al. (2010). Furthermore, the estimated croplands' average WUE value in Ethiopia (1.31 g C mm^{-1}) is slightly higher than its counterpart in China (1.17 g C mm^{-1}) as indicated by Liu et al. (2015) for the years 2000 to 2011, and 54% higher than the global croplands' average WUE value (0.85 g C mm^{-1}) for the period from 1995 to 2004 (Ito and Inatomi, 2012). Notably, the croplands' average WUE value for Sudan (0.18 g C mm^{-1}) is lower than the nationally-averaged annual WUE (2000–2013) of Sudan's terrestrial ecosystems (0.24 g C mm^{-1}) as reported by Khalifa et al. (2018). The variation in climate (air humidity, temperature, evapotranspiration, and precipitation), vegetation conditions, and water supply sufficiency are the main factors determining the WUE of croplands (Liu et al., 2015; Tong et al., 2009; T. Zhang et al., 2016). For instance, Egypt is located in a hyper-arid zone, i.e., high temperatures and extremely limited precipitation throughout the year, which could be the major drivers for its high AET and low NPP values. In contrast, Ethiopia is within the humid, dry subhumid, and arid zones that receive the highest rainfall rates and among the lowest temperatures in the ENC, which may explain the country's higher NPP and WUE values. The Nile Basin Water Resources Atlas (NBWRA, 2020) provides information on the variations of these climatic parameters in the three countries, consistent with and justifies the spatial and temporal WUE variation we observed. The temporal analysis of CV related to WUE reveals high stability in WUE in Egypt and Ethiopia compared to Sudan (Table 5.3). Spatially, CV was less stable in most cropland in Sudan, with values ranging from 50% to 100%. In comparison, there was less variation of WUE in the majority of cropland in Egypt (2–10%) and Ethiopia (5–15%) (Fig. 5.5c). However, statistical trend analysis in WUE over the 16 years indicated no trend in Egypt, an increasing trend in Sudan, and a probable decrease in Ethiopia (Table 5.4).

Table 5.4. Summary of trend analysis of the precipitation (P), net primary productivity (NPP), actual evapotranspiration (AET), water use efficiency (WUE), and crop water productivity (CWP) over the period (2003–2018) in the three studied countries. S = Mann-Kendall Statistic; CL = Confidence Level.

	Egypt		Ethiopia		Sudan	
	S	CL (%)	S	CL (%)	S	CL (%)
P	10	65.5	8	62.2	22	82.5
	No trend		No trend		No trend	
NPP	-12	68.7	6	58.8	40	96.1
	Stable trend		No trend		Increasing trend	
AET	-38	95.2	18	77.5	24	84.7
	Decreasing trend		No trend		No trend	
WUE	20	80.1	-32	91.7	38	95.2
	No trend		Decreasing trend		Increasing trend	
CWP	98	99.9	102	99.9	8	62.2
	Increasing trend		Increasing trend		No trend	

Despite the relatively high WUE values of the Ethiopian croplands found in this study, the yield values were quite low. This observation might be explained by the fact that yield data quantify the final output for specific crops, while NPP is a rate related to the ability of plants to capture carbon dioxide and convert it into biomass, which might include mixed crops with different NPPs. In other words, NPP is only a proxy for biomass and, therefore, it might not be well-correlated with crop yield. CWP analysis revealed considerable variations among the three countries (Table 5.3). On average (2003–2018), Egypt had the highest CWP value (2.54 kg m^{-3}), followed by Ethiopia (0.41 kg m^{-3}) and Sudan (0.23 kg m^{-3}). Previous studies emphasized that the CWP was low in Sudan and Ethiopia compared to Egypt and indicated the latter's average yields for some crops to be among the highest in the world (Al-Saidi et al., 2017; Awulachew et al., 2010; Karimi et al., 2012). Analysis of the CWP time series displayed an increasing trend in Egypt and Ethiopia, while no trend was found in Sudan (Table 5.4). The inter-annual analysis of CWP showed the potential for improvements by estimated CV values of 13%, 10%, and 26% in Sudan, Egypt, and Ethiopia, respectively, emphasizing Egypt's high uniformity.

5.3.5. Percentage of improvement in yield and WFP in vertical scenarios

Based on the potential yield values extracted from the literature and the calculated percentiles of 50% (V-2) and 75% (V-3) of the yield gap, yields of 10% and 15% higher (than attainable values) could be achieved in Egypt in the V-2 and V-3 scenarios, respectively. While in Sudan and Ethiopia, 50–100% and 30–60% higher yield values were considered to be achievable in the V-2 and V-3, respectively.

Regarding the WFP, three possible improvements (10%, 20%, and 30%) were assumed based on the statistical analysis (CV) of WUE and CWP. Although CV values in Egypt were lower than in Sudan and Ethiopia (Section 5.3.4), we assumed equal percentages of improvements for the three countries. Showing the results of these ambitious improvements, particularly in Egypt, would provide policymakers with an outlook for needed policies to realize such highly efficient pathways.

5.3.6. Water resources perspective

Based on AQUASTAT data, the total annual renewable water resources in Ethiopia, Sudan, and Egypt are 122, 37.8, and 57.5 km^3, respectively. These numbers express the long-term average annual river flows and recharge of groundwater aquifers generated from precipitation (blue water), leaving out the rainwater stored in the soil (green water). Furthermore, the total renewable water resources values are a result of summing internal and external blue water resources. Externally, Ethiopia as a water tower receives no water from outside its borders, while 96.5 km^3 leaves the country, i.e., 25.5 km^3 remains within the country. Sudan and Egypt receive blue water quantities of 33.8 and 56.5 km^3, respectively, sourced from the Nile waters. Internally, annual precipitation accounts for 470, 936, and 18 km^3 of rainfall in Sudan, Ethiopia, and Egypt, respectively (AQUASTAT, 2016). Considerable volumes of these precipitation values are available as green water for the rainfed cultivation in Sudan and Ethiopia as reflected by their corresponding P values of 95 and 145 km^3, respectively, compared to Egypt (1.8 km^3) (Section 5.3.2.). Thus, the common use and availability of green water in the rainfed agriculture in Ethiopia and Sudan gives the two countries an advantage over Egypt, from a water resources perspective, since Egypt mainly depends on blue water resources (57.5 km^3) and water reuse systems (≈ additional 19 km^3) to meet its water withdrawals of around 78 km^3.

Although green water is commonly represent by AET (Schyns et al., 2015), we used P (inflow) to represent the green water (Weiskel et al., 2014) since AET over ENC cropland includes contributions from both green and blue water resources. To simplify our calculations and make them consistent, we estimated the total renewable water resources available for croplands as the sum of blue and green water resources, i.e., approximately 170 km^3 (25.5 + 145) in Ethiopia, 133 km^3 (37.8 + 95) in Sudan, and 78 km^3 (57.5 + 1.8 + 19) in Egypt.

5.3.7. Horizontal and vertical scenarios

The future demand for crops indicates that total crop production quantities must be increased by 45%, 59%, and 74% in Egypt, 75%, 90%, and 105% in Sudan, and 67%, 83%, and 100% in Ethiopia, for the low, medium, and high population fertility variants, respectively, to meet the future demand of the estimated population by 2050. Such high values are expected to stand as a future challenge for the three riparian countries.

The developed scenarios reveal the potential for saving substantial water and land resources by 2050 in the ENC by following the vertical development scenarios rather than the horizontal one. The future demands of water and land for each scenario and population variant are presented in Fig. 5.6a and 5.6b. Future forecasts of all scenarios and fertility variants regarding each crop's required water and land resources in the three countries can be found in Appendix B, Tables B3–B8. The vertical scenarios result in a significant reduction in the water demand by 2050 compared to the horizontal one. It is worth mentioning that other water uses, i.e., industrial and domestic, are not presented in Fig. 5.6a, yet, they account for nearly 4%, 8%, and 20% (≈ 0.85, 1.0, and 16 km^3) of water withdrawals in Sudan, Ethiopia, and Egypt, respectively (AQUASTAT, 2016). These withdrawals are additional burdens on water resources, notably in Egypt.

In all scenarios, Egypt is expected to struggle to secure such substantial amounts of water and land with its limited available resources. Both resource types can be considered as limiting factors for ensuring sufficient future production, and projections are expected to cause significant challenges for the Egyptian decision-makers. Cereal cultivation shows the highest demand for resources, representing around 65% and 66% of the total estimated demand for water and land, respectively, followed by fruits (11% and 8%), vegetables (5% and 7%), and sugar crops (7% and 5%). Theoretically, Sudan seems able to afford the required water quantities in all vertical scenarios. However, despite the vast availability of cultivable land (≈ 200,000 km^2), the land required in the horizontal and V-1 scenarios is still much higher. Nevertheless, Sudan can meet the land demand by following V-2 or V-3, which would save the country 53% and 65% of the required land, respectively, compared to the horizontal pathway. Cereals and pulses are expected to require an average of 69% and 25% of total water demand, and 70% and 25% of total needed land, respectively.

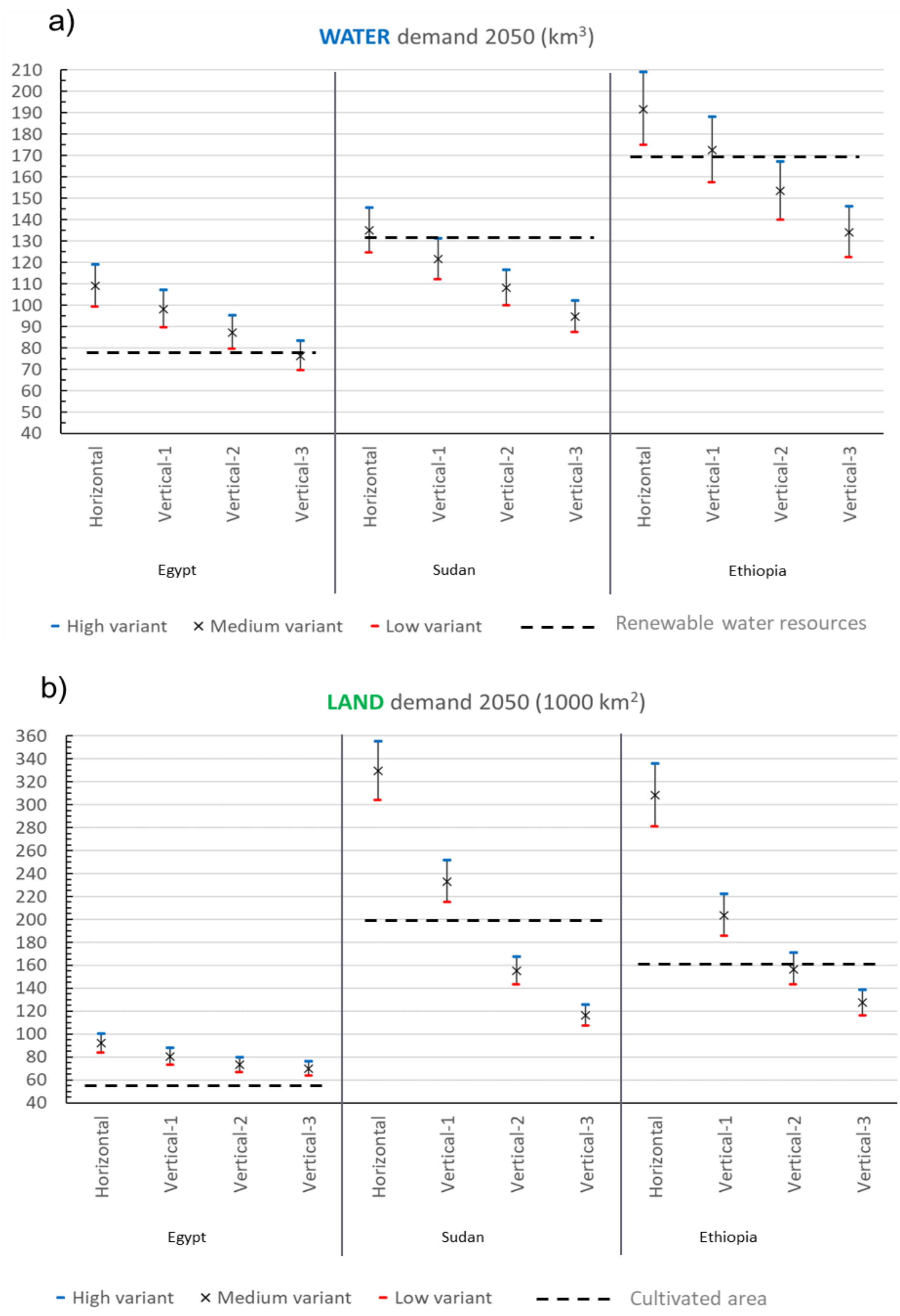

Fig. 5.6. Estimated future demand for (a) water and (b) land of selected crops in each country by 2050 in all scenarios and fertility variants.

The results indicate that a horizontal development pathway will not feasibly meet the future demand for agricultural production in Ethiopia due to water and land constraints. While realizing V-1 could fulfill the water demands of the medium and high variants, its land demand is higher than the country's cultivable area in all variants. However, employing V-2 or V-3 may provide Ethiopia substantial opportunities. Cultivation of cereals, pulses, oil crops, and coffee requires approximately 77%, 7%, 4%, and 4% and 70%, 10%, 5%, and 3% of the total estimated demand of water and land, respectively.

5.3.8. National outlook

Based on the key findings of the current research and assuming that the adopted hypotheses hold, the three countries, especially Egypt, are expected to face severe challenges in satisfying their future demand for the main crops by 2050 due to water and/or land constraints. These results uncover the anticipated challenge to secure water and land resources for sufficient production of the studied crops without accounting for other water uses (e.g., industrial, domestic, and hydropower generation [reservoir evaporation]) that will likely grow. Moreover, climate change is expected to impact the ENC and their resources availability, which may alter the WFP and yield of crops. The length and reliability of the rainy periods will become uncertain due to climate change, which might influence the economics of agriculture, particularly the rainfed agriculture in Sudan and Ethiopia. Similar studies have concluded that future agricultural water demand cannot be solely met by expanding irrigation schemes (Awulachew et al., 2012), improving irrigation efficiency (Multsch et al., 2017), or reallocating water resources (Siderius et al., 2016) in the region.

According to the obtained data on WFP and yield, Egypt is found to have the lowest WFP and highest yield values. This could be attributed to the use of advanced irrigation techniques such as sprinkler or drip irrigation (Al-Saidi et al., 2017), which, together with the water reuse system and the availability of fertilizers and pesticides, may explain the high overall irrigation system efficiency of 81% throughout the country as estimated by Ayyad et al. (2019). However, the estimated numbers in all scenarios suggest that Egypt will need to increase its imported crops and invest more in non-conventional water resources (e.g., water desalination and water and wastewater treatment) as well as in integrated water-energy-food nexus solutions (e.g., agrivoltaic systems) to maintain its production, which requires extensive planning and large investments. The productivity of rainfed agriculture in Sudan and Ethiopia could be significantly improved by adopting strategies for rainwater management, soil conservation, and supplemental irrigation (Rockström et al., 2009). In Ethiopia, Karimi et al. (2012) suggested that poor field practices, and minimal financial resources of farmers to invest in on-farm inputs (e.g., fertilizers and good-quality seeds), are drivers for the low yield values. They also recommended improving water management on the field level and promoting supplementary irrigation, which requires investing in rainwater harvesting techniques and water infrastructures. Khalifa et al. (2020) investigated the determinants of the sorghum yield gap in one of the world's largest irrigated schemes, i.e., the Gezira scheme in Sudan. Their principal findings indicate that farmers' financial statuses, field management practices, and access to water for irrigation exert a major influence on yield. Furthermore, Al Zayed et al. (2015) reported that the Gezira scheme had a low irrigation efficiency, in decline since 1993, caused mainly by the over-supply and leakage in the water delivery system. Khalifa et al. (2020) suggested that improving the efficiency of the scheme—which consumes about one-third of Sudan's total share from the Nile waters—may have significant impacts on stabilizing the water supply and demand in the ENC.

Another opportunity to maximize the potential water and land savings is represented by the substitution of portions of major cereal crops, particularly wheat, for which the three countries depend on imports to meet their domestic demand. For instance, to bridge the wheat gap in Egypt, portions of wheat flour could be substituted by cassava, quinoa, and guar (Soliman et al., 2019) or flour from local cereals and pulses (Zeinab et al., 2018). Studies in Sudan also uncover the potentiality of blending sorghum with wheat products (e.g., Siddeeg et al., 2017). Similarly, for Ethiopia, several studies have proposed the substitution of portions of wheat bread with cassava and soybean flours (Ayele et al., 2017), sweet potato flour (Mitiku et al., 2018), and substituting quinoa flour for teff flour (Agza et al., 2018). Although investigating crop substitution scenarios is outside the scope of the present study, it can be considered a reasonable response to the expected future insufficiencies in water and land resources to secure adequate domestic production of crops.

5.3.9. Transboundary implications

Despite the high potential for saving water and land by following the vertical development pathway demonstrated in this study, a more ambitious scenario is possible—a regional benefit-sharing approach. For instance, there is a potential for expanding and increasing irrigated areas, particularly in Sudan and Ethiopia (Awulachew et al., 2012; Hamouda et al., 2009), but doing this will place Egypt in a vulnerable position by reducing its water by almost 40%, as estimated by Siderius et al. (2016). In this regard, we aim to shed light on possibilities that could benefit the three riparian countries while setting aside geopolitical issues. The three countries can, theoretically, maximize the regional benefits by identifying their particular competencies. For example, producing some crops in Egypt, such as wheat and sorghum, seems very efficient, given their high yield and optimum WFP values. In detail, WFPs for producing wheat and sorghum in Egypt are 1692 and 1107 m^3 ton^{-1}, respectively, which are much less than their counterparts in Sudan (1929 and 6521 m^3 ton^{-1}), Ethiopia (3679 and 5007 m^3 ton^{-1}), and even the world average (1827 and 3048 m^3 ton^{-1}). In addition, the WFP of millet in Ethiopia (4842 m^3 ton^{-1}) is much less than its counterpart in Sudan (13,616 m^3 ton^{-1}). Furthermore, yield values reveal high variations among the three countries for some common crops. For example, the average yield values for wheat and sorghum are approximately 623 and 533 ton km^{-2} in Egypt, 215 and 61 ton km^{-2} in Sudan, and 170 and 175 ton km^{-2} in Ethiopia. The overall average yield values for the studied crops in Egypt, Sudan, and Ethiopia are 1990, 831, and 215 ton km^{-2}, respectively. Utilizing the Egyptian experience and advanced technology in existing and planned irrigated schemes in Sudan and Ethiopia can significantly contribute to improving these schemes' productivity and, thus, productivity in the ENC as a whole. In the same context, allocating regional investments towards improving the irrigation efficiency and productivity in existing and planned irrigated schemes in Sudan—the country with the largest reserve of cultivable land within the ENC—might be crucial to maintain the production of some crops in the region (e.g., sorghum and wheat). Ethiopia has the advantage in hydropower and livestock production, which could act as affordable energy and meat products for Egypt and Sudan.

Sharing the benefits of using the Nile waters beyond the political boundaries is not only possible but might also be a necessity. Since the commencement of its construction in 2011, Ethiopia, Sudan, and Egypt have been engaged in negotiations regarding the Grand Ethiopian Renaissance Dam (GERD). Yet, no agreement has been reached as of the time of writing this article. A crucial outcome of the recent negotiations is that the three countries shall work on a comprehensive agreement concerning the Blue Nile waters and its future developments (African Union, 2020). Such an agreement can be guided by forecasts of multiple development scenarios, among other principles. We believe that the findings of the present study can help steer future negotiations among the three riparian countries by quantifying their anticipated water and/or land deficits by 2050. Besides the guiding forecasts, an atmosphere of goodwill from the three riparian nations is needed to achieve win-win solutions. To realize this scenario while achieving a reasonable and equitable utilization of the shared water resources, policymakers of the three countries might need to consider using the concepts of WFP, yield gap, and virtual water as measuring tools or indicators for resources utilization (e.g., Sallam, 2014; Zeitoun et al., 2010). Benefit-sharing would also require a more comprehensive political, environmental, and socio-economic assessment. Furthermore, improvements in data monitoring, quality, availability, accessibility, and sharing within the three riparian countries are crucial for the sustainable development of the region. Although a thorough discussion of a regional benefit-sharing is beyond the scope of this study, the reported results form the basis to investigate the potential of such a scenario, which would contribute significantly to maintain the agricultural production in the ENC.

5.3.10. Limitations and future research

One of the major limitations that researchers commonly face is the validation of remote sensing datasets. In the present study, it was not feasible to validate the selected remote sensing datasets due to the sparse data for ground-truthing in the ENC and the mismatches between gridded satellite-based information and ground information. While some of the selected products perform well, as explained in the referenced literature in Sections 5.2.3.3 and 5.2.3.5, future research may evaluate more products in the region, particularly for NPP, AET, and land cover. One drawback of the current research is the lack of detailed crop type maps that distinguish between different crops cultivated in each country. Consequently, the calculated P, NPP, AET, and WUE are estimated from satellites for crop groups. The uncertainty involved in dealing with the whole croplands as one unit involves further uncertainties in the estimated AET, NPP, and WUE. Since different crops are characterized by distinctive NPP, AET, and WUE, our estimated indicators are rather general. Nevertheless, the datasets adopted are crucial for understanding the croplands' spatial and temporal patterns and their performance in such a data-scarce region. The results reported herein should be interpreted in that light.

Future research may investigate the costs associated with improving the WFP and yield values as indicated in the proposed vertical scenarios to enable decision-makers to identify the optimal development pathway. Furthermore, it is worthwhile to explore a regional benefit-sharing scenario, based on the yield gap, WFP, and favorable trade agreements. Although the current agricultural water withdrawals in South Sudan (0.25 km^3) and Eritrea (0.55 km^3) were neglected in this study, the two countries might introduce plans for developing irrigation projects and, subsequently, their demand for water and land may increase in the future. Therefore, future ENC assessments may need to account for these potential demands.

Our findings fundamentally demonstrate the urgent need for sustainable agricultural intensification in the three countries to sustain their crop production through 2050. However, critics and debates of agricultural intensification have been raised to address negative impacts associated with such production systems (e.g., Godfray, 2015; Pretty and Bharucha, 2014), which should be considered in future planning.

5.4. Conclusions

In this study, with the assistance of remote sensing data, the spatio-temporal variations (2003–2018) of a set of indicators (i.e., cropland area, P, NPP, AET, WUE, and CWP) over cropland in the ENC were observed. Our findings indicated high variations in these indicators throughout the ENC and their inter-annual variation and trends were investigated. Subsequently, we estimated the prospects of improvements in WFP. Furthermore, yield gaps were estimated, and percentages for possible yield improvements were consequently identified.

The hypothesis herein is that a vertical growth pathway (intensification), achieved by reducing the WFP and bridging the yield gap of the major crops, is more feasible in terms of saving water and land resources and could provide more crops than what is expected by following the horizontal growth pathway (expanding the cultivated land). To test our hypothesis, we proposed four development scenarios and quantified the demand for water and land resources for sufficient crop production in each country and scenario by 2050.

Our findings indicate that the three countries are expected to face a severe challenge in securing sufficient crop production from the available water and land resources. Nevertheless, substantial water and land resources could be conserved by 2050 by following the vertical development scenarios rather than the horizontal one. The main achievements of this study are:

- Using remote sensing to detect cropland changes and variation patterns of P, AET, NPP, and the calculated WUE and CWP provides unprecedented spatial representation that cannot be achieved using *in-situ* measurements.
- Emphasizing the crucial role that agriculture plays in the ENC. Moreover, the scenario-based analysis of the development pathways highlights the critical implications of these pathways for water and land resources.
- The expected deficit in water and/or land resources by 2050 in the ENC, as depicted in most future scenarios, is alarming. Although the benefits of following a vertical development pathway in the agriculture sector in the ENC are apparent, this study is the first to quantify and put these benefits in the transboundary context. These figures have large implications on the water and food securities, land cover change policies, and natural resources management in general, especially water and land.

Our study stresses the potential advantages of benefits and resources sharing, based on the WFP, yield gap, and trade between the three countries to secure water and food beyond the political boundaries. Based on the current research results, shifting from resource-sharing to benefit-sharing seems to be not only feasible but also necessary to ensure sustainable development in such a vital and conflicted region.

As poor agriculture performance is not restricted to the ENC, the findings of this research are useful for many other parts of the world, especially where the use of water and land resources needs to be optimized. Lastly, the methods used in this study are transferable and could be applied in any other region facing similar fundamental development questions.

Acknowledgments

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6. General discussion and conclusions

6.1. Synopsis

In Africa, agriculture is not only a major user of blue and green freshwater and land resources, but also the primary source of livelihood for the African population. With the continent experiencing rapid population growth and consequent increased food and livelihood demands, recent change trends comprise the expansion of cropland areas, leading to greater use of water and land resources, a development strategy known as agricultural extensification. This thesis stresses the pressing need for agricultural intensification, emphasizing the enhancement of productivity on existing croplands.

The primary objective of this thesis was to identify and quantify the potential for increasing crop yield and conserving water and land resources across selected case studies in Egypt, Sudan, Ethiopia, and Tanzania, representing various types of agricultural systems that rely on blue and green water resources. Additionally, the thesis aimed at providing insights into the implications of potential improvements for future crop intensification and the associated demands for water and land resources. To achieve these multidisciplinary aims in such data-scarce regions, this research developed novel methodological approaches, integrating open-access remote sensing and secondary datasets. The study generated valuable insights into potential improvements in crop production systems across the case studies, as detailed in Chapters 3, 4, and 5.

6.2. Revisiting hypotheses and findings

This section discusses the key elements and findings of Chapters 3, 4, and 5 in relation to the main research hypotheses formulated in Chapter 1 as follows:

- **Hypothesis (i):** Open-access remote sensing datasets can support improving investigations on agricultural systems in data-scarce regions.

A consistent obstacle encountered in the investigated case studies is the scarcity of *in-situ* data that, when available and accessible, fails to capture or explain spatial variations across larger areas or temporal changes over time. Satellite-based remote sensing technology has made it possible to accurately monitor agricultural systems and associated parameters such as land use, land cover, precipitation, actual and potential evapotranspiration, crop yield, and transpiration, at adequate spatial and temporal resolutions. The use of such remote sensing datasets for monitoring these parameters is well established in the scientific community.

However, the novel methodological approaches developed here, involving the use and integration of available remote sensing datasets with secondary data, provided in-depth insights into the performance of agricultural systems. This is particularly evident when calculating performance indicators such as water use efficiency, crop water productivity, land productivity, evaporative stress, relative evaporative stress, and transpiration fraction, all at adequate spatial and temporal resolutions across case studies of diverse agricultural types, scales, challenges, and scenarios, as demonstrated in this thesis. It is worth noting that, while commercial remote sensing datasets are available for purchase, this thesis advocates for the use of open-access datasets that are freely accessible through public-domain sources. This is particularly crucial in developing regions of Africa to support the democratization of knowledge and to empower researchers, decision-makers, and local communities to verify findings, reproduce results, and address pressing challenges to shape more sustainable futures.

- **Hypothesis (ii):** A comprehensive spatial-temporal investigation of crop production systems will enable understanding the current performance status and detecting potential improvements.

This thesis aimed at detecting opportunities for increasing crop yield and conserving water and land resources across the three selected case studies. A comprehensive monitoring of agricultural performance that considers both temporal and spatial dimensions was required to spot such opportunities. For instance, remote sensing datasets were used here to analyze crop production performance over timespans of 20 years in Kilombero, five years in the Nile Delta, and 16 years in the Eastern Nile countries. Moreover, large spatial extents were covered to capture the spatial variability across these regions. Across the three investigated cases, spatial and temporal variations were observed, as indicated by the coefficient of variation values. In essence, had the analyses been limited to specific locations and timespans, the representativeness of the results obtained, and consequently the validity of conclusions drawn, would have been questionable. By investigating the spatial and temporal change dynamics of crop production systems over adequate timespans and spatial scopes, the thesis could derive rational results and conclusions regarding the performance status and the potential improvements by addressing the observed spatial and temporal variabilities. Moreover, the present spatial-temporal investigations can serve as references when interpreting results of future studies targeting relevant questions within the spatial and temporal scopes covered of this research.

- **Hypothesis (iii):** Quantifying potential improvements in crop production and water use systems can help construct plausible future scenarios of crop intensification and associated water and land requirements.

To construct plausible and realistic scenarios of future crop intensification, it was imperative to comprehensively detect and quantify potential improvements in existing crop production and water use systems. In this thesis, potential improvements were thoroughly explored and served as the major variables for constructing future scenarios of agricultural intensification and associated demand for water and land resources. For example, as detailed in Chapter 4, the research findings demonstrated the potential for improving crop yield, transpiration fraction, and crop water productivity in the Nile Delta by up to 27, 4, and 14%, respectively. These detected improvements constituted the key input variables in developing scenarios projecting Egypt's water and land requirements for sustaining domestic crop production until 2050. Chapter 5 adopted a comparable approach and detected improvements in crop yield and water footprint of up to, respectively, 15 and 10% in Egypt, 100 and 30% in Sudan, and 60 and 26% in Ethiopia. These improvements, along with various population growth scenarios, were subsequently used as primary input variables in the developed scenarios projecting future demands for water and land until 2050 in the three countries. Finally, the findings presented in Chapter 3 demonstrated the potential for dry season cultivation within the pre-rice (70 days) and post-rice (65 days) niches using available green water over at least 53% of the total cropped area in the Kilombero Valley Floodplain. This enabled the envisioning of possible cropping options that fit well with the pre- and post-rice niches. Without the detection of potential improvements in crop production and water use systems, it would have been necessary to rely on arbitrary assumptions or normative values for key variables required to construct future scenarios of intensification. This, in turn, would have introduced further uncertainties to the results obtained and their validity.

- **Hypothesis (iv):** The spatial-temporal analysis will permit pinpointing interventions to enhance production efficiency and to conserve water and land resources.

The findings of the spatial-temporal analyses in the three case studies not only enabled the detection of potential improvements in performance indicators but also underscored parameters and areas requiring interventions. For instance, the analysis in Kilombero revealed that water interannual variability, not availability, posed the main challenge in the pre-rice niche, and thus supplemental irrigation was proposed. In the post-rice niche, where available water is less variable over time, recession cropping possibly with supplemental irrigation was proposed. In both the pre- and post-rice niches, high spatial variability in water availability and interannual variability was observed across the cropland extent in Kilombero, delineating areas with different potential for dry season cultivation. In the Nile Delta, the analyzed indicators highlighted opportunities for improving specific parameters. The findings indicated limited potential for enhancing the transpiration fraction. Instead, improving crop yield and water productivity emerged as a more compelling course of action. Furthermore, interventions aimed at increasing crop yield and water productivity would benefit more summer crops (rice and maize) than winter crops (wheat and berseem). Similarly, the findings of the Eastern Nile countries guided both national and transboundary interventions. With its high crop yields and low water footprints, it was suggested that Egypt could augment its food imports and expand its non-conventional water resources, alongside implementing integrated water-energy-food solutions to sustain crop production. In Sudan and Ethiopia, interventions should focus on enhancing crop yields and water footprints, by adopting strategies such as rainwater management, soil conservation, supplemental irrigation, and improving farmers' financial capacities to invest in farm inputs. Additionally, it was recommended to adopt a transboundary regional benefit-sharing approach based on availability of national technical, natural, and financial resources and indicators such as crop yield and water footprint.

6.3. Outlook and recommendations

This thesis addressed the potential of crop intensification by means of increasing crop yield and conserving input resources of water and land over selected case studies in East and North Africa. It introduced novel methodological approaches based on entirely open-access datasets to explore this potential. The studied agricultural systems represent diverse agricultural practices, including irrigation using blue water and rainfed farming relying on green water. These systems also encounter various challenges such as water availability, variability, and scarcity, and encompass different spatial scales including irrigation scheme, floodplain wetland, national, and transboundary levels. Despite the diverse nature of these systems, the developed approaches proved instrumental in analyzing the performance status of existing agricultural systems, detecting and quantifying potential improvements, constructing future scenarios for land use intensification along with associated water and land demands, and pinpointing necessary interventions.

Given the pressing need to enhance food security in Africa, efforts aiming at the further development of such methodological approaches should continue to provide decision-makers with outlooks on plausible pathways for crop intensification. It is also important to continue providing and using open-access datasets to foster access to knowledge, allow for reproducibility and transferability, and empower researchers, policymakers, and the public alike to formulate evidence-based policies and strategies for addressing pressing challenges in Africa. While the methodological approaches and datasets used in this thesis are transferable and can be applied in other regions, it is advisable to adapt and refine these approaches and datasets according to the specific research demands in the target regions. Furthermore, operationalizing such methodologies is essential to enable continuous monitoring of performance of crop production systems and assess impacts of implemented interventions. Beyond the biophysical assessment conducted in this research, it is recommended to undertake further investigations into geographical areas exhibiting notably good or deficient performance across the case studies. This is crucial to help identify the causes of performance variation over time and space, and to understand the real-world determinants of crop intensification, including socioeconomic, technological, and aspirational and behavioral factors, among others. Such comprehensive assessments are vital for envisioning evidence-based and achievable pathways for sustainable agricultural development in Africa.

The findings of this thesis underscore the considerable potential for crop intensification within the studied regions. The potential improvements identified hold profound implications for water and food security, as well as for the sustainable management of water and land resources. They also represent pivotal entry points for guiding interventions and investments aimed at enhancing crop production and conserving vital water and land resources. The valuable insights revealed can inform strategic decision-making processes and direct initiatives towards pathways for agricultural sustainability and resilience in Africa. Therefore, fostering regional and international cooperation and encouraging initiatives aimed at implementing the research and actions recommended here is imperative. Moreover, promoting innovation and technology transfer is important to equip agricultural stakeholders with the essential tools and knowledge to effectively develop region-specific sustainable practices and solutions that are tailored to the unique challenges faced by the region. To achieving these goals, it is necessary to mobilize sufficient funds, build the capacities of African institutions and initiatives, empower institutional commitments, foster public-private partnerships, and demonstrate political will to change the present status in the face of evolving environmental and socio-economic challenges in Africa. Ultimately, achieving agricultural sustainable intensification and improving water and food security in Africa requires a comprehensive and multi-dimensional approach that addresses the interlinkages of the social, political, economic, and environmental challenges facing the continent. By prioritizing collaboration, innovation, and inclusive governance and decision-making in resource management, Africa can unlock its agricultural potential and pave the way for more resilient and prosperous agricultural futures.

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Appendices

Appendix A

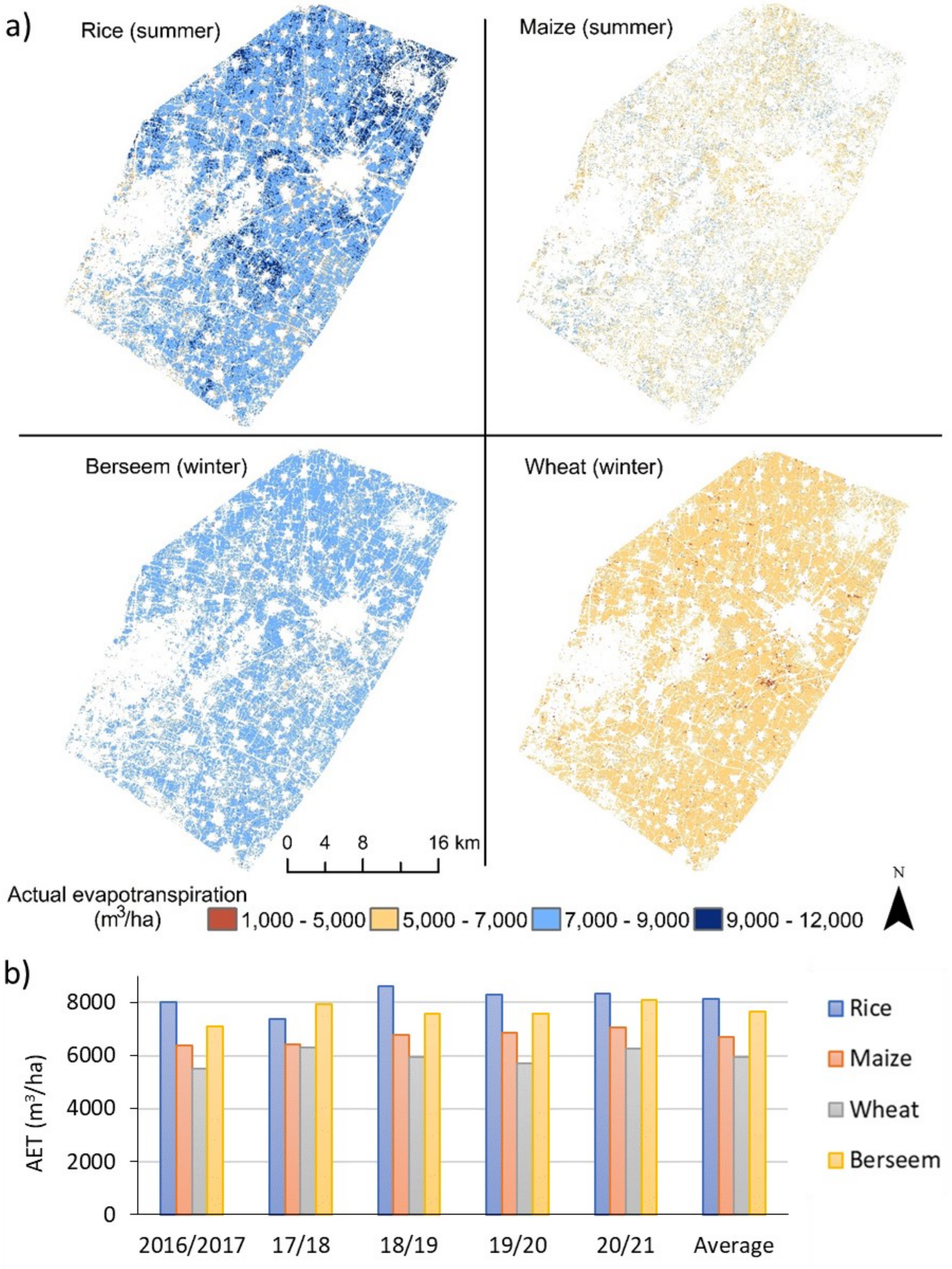

Fig. A1. a) Spatial variation of seasonal actual evapotranspiration for the studied crops in Zankalon (average of 2016–2021). b) Seasonal and 5-year average estimates. Data derived from WaPOR.

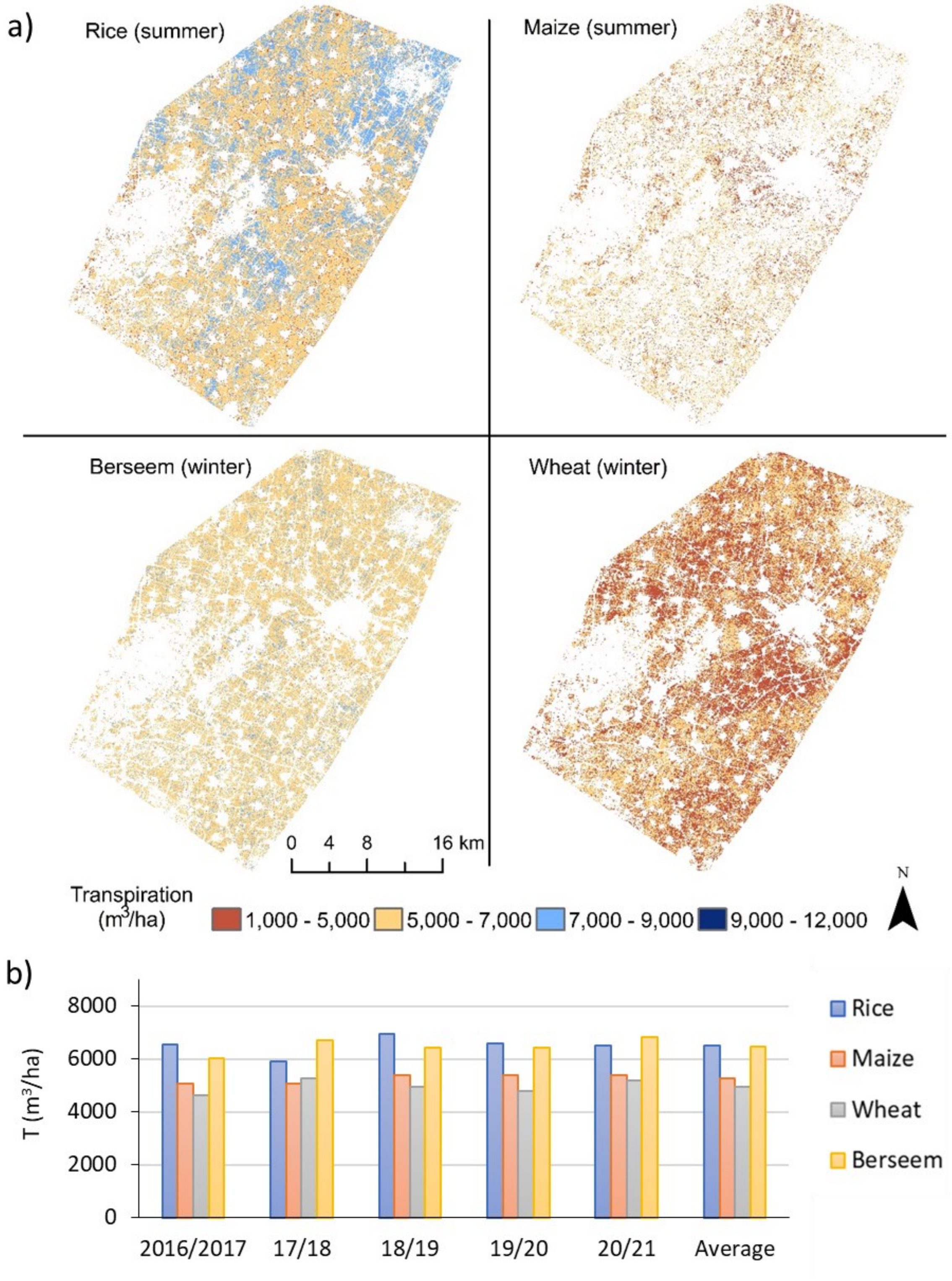

Fig. A2. a) Spatial variation of seasonal transpiration for the studied crops in Zankalon (average of 2016–2021). b) Seasonal and 5-year average estimates. Data derived from WaPOR.

Appendix B

Table B1. Selected crops in each country (included crops are marked with X).

Crop category	FAO-code	Crop name	Egypt	Sudan	Ethiopia
Cereals	15	Wheat	X	X	X
	83	Sorghum	X	X	X
	56	Maize	X		X
	27	Rice	X		
	44	Barley	X		X
	71	Rye	X		
	79	Millet		X	X
	108	Teff (cereals nes)			X
Pulses	195	Cow peas, dry		X	
	211	Pulses nes		X	
	181	Broad beans, horse beans, dry	X	X	X
	191	Chick peas			X
	176	Beans, dry	X		X
	201	Lentils			X
	187	Peas, dry			X
	205	Vetches			X
Oil crops	242	Groundnuts, with shell	X	X	X
	289	Sesame seed		X	X
	299	Melon seed		X	
	267	Sunflower seed		X	
	333	Linseed			X
	339	Oilseeds nes			X
	260	Olives	X		
Vegetables	388	Tomatoes	X		
	403	Onions, dry	X	X	
	399	Eggplants	X		
	463	Vegetables, fresh nes	X		X
Roots and tubers	116	Potatoes	X		X
	122	Sweet potatoes			X
	149	Roots and tubers nes			X
	137	Yams		X	
Fiber crops	328	Seed cotton	X	X	X
	821	Fibre crops nes			X
Sugar crops	156	Sugar cane	X	X	
	157	Sugar beet	X		
Pimento	689	Chillies and peppers, dry			X
Coffee	656	Coffee, green			X
Fruits	490	Oranges	X		
	571	Mangoes, mangosteens, guavas	X		
	577	Dates	X		
	560	Grapes	X		
	567	Watermelons	X		
	568	Melons, other	X		
	495	Tangerines, mandarins, clementines, satsumas	X		

Table B2. Summarized review of studies estimating potential yield of main crops in the three countries.

Country	Crop	Study	Method	Potential yield (ton ha^{-1})	Yield gap (%)[a]
Egypt	Rice	[1]	On-station experiments & crop modelling	11.6	13
		[2]	Field experiment	11	8
	Wheat	[3]	Field experiment	9.8	30
			Crop modelling	8	14
		[4]	Field experiment	7.8–8.9	12–23
		[5]	Crop modelling	8.04	15
	Maize	[4]	Field experiment	9.6–12.2	13–31
		[6]	Census data	8.66	3
Sudan	Sorghum	[7]	Field experiment	2–4	62–81
		[8]	Field experiment	2.5–3.8	70–80
		[9]	Census data	0.85–1.5	10–49
	Millet	[9]	Census data	3.6	80
	Wheat	[10]	Field experiment	3.9	2
		[11]	Demonstration plots	3.9–5.1	2–25
		[12]	Field experiment	4.2–5.9	9–35
		[9]	Census data	4.1	7
Ethiopia	Teff	[13]	Field research	2.7	36
		[14]	Field experiment	3	43
		[15]	Statistics econometrics models	1.95	12
	Maize	[16]	On-farm and on-station trials	4.59	19
		[17]	On-farm and on-station experiments	8–12	53-69
			Crop modelling	15.66	76
		[18]	Household survey and crop models	6.3–18.1	41-79
		[19]	Household survey	6.1	39
		[20]	Field experiment	12.7–13.1	71
		[21]	Crop modelling	9.2	59
	Wheat	[17]	On-farm and on-station experiments	5–5.5	44-49
			Crop modelling	9.59	71
		[22]	On-farm and on-station trials	6–7	53-60
	Barley	[23]	Field survey	3.2–4.3	32-50
		[24,25]	Field experiment	6	64
	Millet	[17]	On-farm and on-station experiments	2.9–3.1	23-28
			Crop modelling	5.97	63
	Sorghum	[17]	On-farm and on-station experiments	3.3–4.2	18-36
			Crop modelling	9.05	70
		[16]	On-farm and on-station experiments	4.26	37

[a] Yield gap (%) = [(potential – attainable)/potential]*100

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Table B3. Required water quantities (in km^3) of crops by 2050 in Egypt in all scenarios (numbers are rounded to the nearest tenth).

Crop	Low fertility variant				Medium fertility variant				High fertility variant			
	H	V-1	V-2	V-3	H	V-1	V-2	V-3	H	V-1	V-2	V-3
Wheat	23.4	21.0	18.7	16.4	25.7	23.1	20.5	18.0	28.1	25.2	22.4	19.6
Rice	20.7	18.6	16.5	14.5	22.7	20.4	18.1	15.9	24.8	22.3	19.8	17.3
Maize	17.6	15.8	14.1	12.3	19.3	17.4	15.4	13.5	21.1	19.0	16.9	14.8
Sorghum	1.7	1.6	1.4	1.2	1.9	1.7	1.5	1.3	2.1	1.9	1.7	1.5
Barley	0.8	0.7	0.7	0.6	0.9	0.8	0.7	0.6	1.0	0.9	0.8	0.7
Rye	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.1
Beans, dry	0.4	0.3	0.3	0.2	0.4	0.3	0.3	0.3	0.4	0.4	0.3	0.3
Broad beans, horse beans, dry	1.5	1.3	1.2	1.0	1.6	1.4	1.3	1.1	1.8	1.6	1.4	1.2
Tomatoes	3.2	2.9	2.6	2.2	3.5	3.2	2.8	2.5	3.9	3.5	3.1	2.7
Onions, dry	0.9	0.8	0.7	0.6	1.0	0.9	0.8	0.7	1.1	1.0	0.9	0.7
Eggplants	0.6	0.6	0.5	0.4	0.7	0.6	0.6	0.5	0.8	0.7	0.6	0.5
Vegetables, fresh nes	0.4	0.4	0.3	0.3	0.4	0.4	0.3	0.3	0.5	0.4	0.4	0.3
Seed cotton	1.7	1.5	1.3	1.2	1.8	1.7	1.5	1.3	2.0	1.8	1.6	1.4
Groundnuts, with shell	1.2	1.0	0.9	0.8	1.3	1.1	1.0	0.9	1.4	1.3	1.1	1.0
Olives	1.6	1.4	1.2	1.1	1.7	1.5	1.4	1.2	1.9	1.7	1.5	1.3
Potatoes	2.4	2.1	1.9	1.7	2.6	2.3	2.1	1.8	2.8	2.6	2.3	2.0
Oranges	3.0	2.7	2.4	2.1	3.3	3.0	2.7	2.3	3.6	3.3	2.9	2.5
Tangerines, mandarins, clementines, satsumas	1.0	0.9	0.8	0.7	1.0	0.9	0.8	0.7	1.1	1.0	0.9	0.8
Dates	0.4	0.3	0.3	0.2	0.4	0.3	0.3	0.3	0.4	0.4	0.3	0.3
Grapes	0.5	0.5	0.4	0.4	0.6	0.5	0.5	0.4	0.7	0.6	0.5	0.5
Mangoes, mangosteens, guavas	1.7	1.5	1.3	1.2	1.8	1.6	1.5	1.3	2.0	1.8	1.6	1.4
Melons, other	2.3	2.1	1.8	1.6	2.5	2.3	2.0	1.8	2.8	2.5	2.2	1.9
Watermelons	5.0	4.5	4.0	3.5	5.5	4.9	4.4	3.8	6.0	5.4	4.8	4.2
Sugar cane	5.4	4.8	4.3	3.8	5.9	5.3	4.7	4.1	6.4	5.8	5.1	4.5
Sugar beet	2.1	1.9	1.7	1.5	2.3	2.1	1.9	1.6	2.6	2.3	2.0	1.8
Total	99.4	89.4	79.5	69.5	109.1	98.2	87.3	76.4	119.2	107.3	95.4	83.5

H: Horizontal scenario, V-1: Vertical scenario-1, V-2: Vertical scenario-2, V-3: Vertical scenario-3

Table B4. Required land areas (in 1000 km^2) of crops by 2050 in Egypt in all scenarios (numbers are rounded to the nearest tenth).

Crop	**Low fertility variant**				**Medium fertility variant**				**High fertility variant**			
	H	**V-1**	**V-2**	**V-3**	**H**	**V-1**	**V-2**	**V-3**	**H**	**V-1**	**V-2**	**V-3**
Wheat	22.2	20.1	18.3	17.5	24.3	22.1	20.1	19.2	26.6	24.2	22.0	21.0
Rice	11.5	10.5	9.6	9.2	12.7	11.6	10.5	10.0	13.9	12.6	11.5	11.0
Maize	16.9	15.1	13.7	13.1	18.6	16.6	15.1	14.4	20.3	18.1	16.5	15.8
Sorghum	2.9	2.7	2.5	2.3	3.2	3.0	2.7	2.6	3.5	3.2	2.9	2.8
Barley	1.1	0.7	0.6	0.6	1.3	0.7	0.7	0.6	1.4	0.8	0.7	0.7
Rye	0.5	0.5	0.5	0.5	0.6	0.6	0.5	0.5	0.6	0.6	0.6	0.5
Beans, dry	0.4	0.4	0.3	0.3	0.4	0.4	0.4	0.3	0.5	0.4	0.4	0.4
Broad beans, horse beans, dry	1.8	1.7	1.5	1.4	2.0	1.8	1.6	1.6	2.2	2.0	1.8	1.7
Tomatoes	3.7	3.3	3.0	2.9	4.0	3.7	3.3	3.2	4.4	4.0	3.6	3.5
Onions, dry	0.8	0.5	0.5	0.4	0.9	0.6	0.5	0.5	1.0	0.6	0.6	0.5
Eggplants	0.7	0.6	0.5	0.5	0.8	0.6	0.6	0.6	0.9	0.7	0.6	0.6
Vegetables, fresh nes	1.0	0.5	0.5	0.4	1.1	0.6	0.5	0.5	1.3	0.6	0.6	0.5
Seed cotton	4.4	3.2	2.9	2.8	4.8	3.5	3.2	3.0	5.3	3.8	3.5	3.3
Groundnuts, with shell	1.1	0.9	0.8	0.8	1.2	1.0	0.9	0.9	1.3	1.1	1.0	1.0
Olives	0.9	0.6	0.6	0.6	1.0	0.7	0.6	0.6	1.1	0.8	0.7	0.7
Potatoes	2.3	2.0	1.8	1.8	2.5	2.2	2.0	1.9	2.7	2.4	2.2	2.1
Oranges	1.9	1.6	1.4	1.4	2.0	1.7	1.6	1.5	2.2	1.9	1.7	1.6
Tangerines, mandarins, clementines, satsumas	0.7	0.6	0.5	0.5	0.8	0.6	0.6	0.5	0.9	0.7	0.6	0.6
Dates	0.7	0.6	0.5	0.5	0.7	0.6	0.6	0.5	0.8	0.7	0.6	0.6
Grapes	1.2	1.0	0.9	0.9	1.3	1.1	1.0	0.9	1.4	1.2	1.1	1.0
Mangoes, mangosteens, guavas	1.0	0.8	0.7	0.7	1.1	0.8	0.8	0.7	1.2	0.9	0.8	0.8
Melons, other	0.6	0.5	0.4	0.4	0.6	0.5	0.5	0.5	0.7	0.6	0.5	0.5
Watermelons	1.1	0.9	0.8	0.8	1.2	1.0	0.9	0.8	1.3	1.0	1.0	0.9
Sugar cane	2.6	2.4	2.2	2.1	2.8	2.7	2.4	2.3	3.1	2.9	2.6	2.5
Sugar beet	1.9	1.6	1.4	1.4	2.1	1.7	1.6	1.5	2.3	1.9	1.7	1.6
Total	83.9	73.2	66.5	63.6	92.1	80.4	73.1	69.9	100.6	87.8	79.8	76.4

H: Horizontal scenario, V-1: Vertical scenario-1, V-2: Vertical scenario-2, V-3: Vertical scenario-3

Table B5. Required water quantities (in km^3) of crops by 2050 in Sudan in all scenarios (numbers are rounded to the nearest tenth).

Crop	**Low fertility variant**				**Medium fertility variant**				**High fertility variant**			
	H	**V-1**	**V-2**	**V-3**	**H**	**V-1**	**V-2**	**V-3**	**H**	**V-1**	**V-2**	**V-3**
Sorghum	60.2	54.1	48.1	42.1	65.2	58.7	52.2	45.7	70.4	63.3	56.3	49.3
Millet	23.5	21.1	18.8	16.4	25.4	22.9	20.4	17.8	27.5	24.7	22.0	19.2
Wheat	2.2	2.0	1.7	1.5	2.4	2.1	1.9	1.6	2.5	2.3	2.0	1.8
Cow peas, dry	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1
Pulses nes	0.4	0.4	0.3	0.3	0.4	0.4	0.4	0.3	0.5	0.4	0.4	0.3
Broad beans, horse beans, dry	0.6	0.6	0.5	0.4	0.7	0.6	0.5	0.5	0.7	0.7	0.6	0.5
Onions, dry	1.9	1.7	1.5	1.4	2.1	1.9	1.7	1.5	2.3	2.0	1.8	1.6
Seed cotton	1.1	0.9	0.8	0.7	1.1	1.0	0.9	0.8	1.2	1.1	1.0	0.9
Groundnuts, with shell	20.5	18.4	16.4	14.3	22.2	20.0	17.8	15.5	24.0	21.6	19.2	16.8
Sesame seed	7.8	7.1	6.3	5.5	8.5	7.7	6.8	6.0	9.2	8.3	7.3	6.4
Melon seed	1.1	1.0	0.9	0.8	1.2	1.1	1.0	0.8	1.3	1.2	1.0	0.9
Sunflower seed	1.3	1.1	1.0	0.9	1.4	1.2	1.1	1.0	1.5	1.3	1.2	1.0
Yams	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.2	0.2	0.1	0.1
Sugar cane	3.9	3.5	3.1	2.7	4.2	3.8	3.4	2.9	4.5	4.1	3.6	3.2
Total	124.7	112.2	99.7	87.3	135.2	121.7	108.1	94.6	145.8	131.3	116.7	102.1

H: Horizontal scenario, V-1: Vertical scenario-1, V-2: Vertical scenario-2, V-3: Vertical scenario-3

Table B6. Required land areas (in 1000 km^2) of crops by 2050 in Sudan in all scenarios (numbers are rounded to the nearest tenth).

Crop	**Low fertility variant**				**Medium fertility variant**				**High fertility variant**			
	H	**V-1**	**V-2**	**V-3**	**H**	**V-1**	**V-2**	**V-3**	**H**	**V-1**	**V-2**	**V-3**
Sorghum	150.7	120.4	80.3	60.2	163.4	130.5	87.0	65.3	176.3	140.8	93.9	70.4
Millet	57.4	24.4	16.3	12.2	62.2	26.5	17.7	13.2	67.1	28.6	19.1	14.3
Wheat	5.2	2.9	2.0	1.5	5.7	3.2	2.1	1.6	6.1	3.4	2.3	1.7
Cow peas, dry	2.2	1.2	0.8	0.6	2.4	1.3	0.9	0.6	2.6	1.4	0.9	0.7
Pulses nes	2.1	2.1	1.4	1.0	2.3	2.3	1.5	1.1	2.5	2.4	1.6	1.2
Broad beans, horse beans, dry	1.4	1.0	0.7	0.5	1.5	1.1	0.7	0.5	1.6	1.1	0.8	0.6
Onions, dry	1.1	0.8	0.5	0.4	1.2	0.8	0.5	0.4	1.3	0.9	0.6	0.4
Seed cotton	3.4	2.3	1.6	1.2	3.7	2.5	1.7	1.3	4.0	2.7	1.8	1.4
Groundnuts, with shell	32.7	24.8	16.5	12.4	35.5	26.9	17.9	13.4	38.3	29.0	19.3	14.5
Sesame seed	40.6	29.9	19.9	14.9	44.0	32.4	21.6	16.2	47.4	35.0	23.3	17.5
Melon seed	2.4	1.8	1.2	0.9	2.6	2.0	1.3	1.0	2.8	2.1	1.4	1.1
Sunflower seed	1.5	0.8	0.6	0.4	1.6	0.9	0.6	0.5	1.8	1.0	0.7	0.5
Yams	1.5	1.3	0.8	0.6	1.6	1.4	0.9	0.7	1.7	1.5	1.0	0.7
Sugar cane	1.6	1.3	0.9	0.7	1.8	1.5	1.0	0.7	1.9	1.6	1.0	0.8
Total	303.9	215.0	143.3	107.5	329.5	233.1	155.4	116.6	355.5	251.5	167.7	125.8

H: Horizontal scenario, V-1: Vertical scenario-1, V-2: Vertical scenario-2, V-3: Vertical scenario-3

Table B7. Required water quantities (in km^3) of crops by 2050 in Ethiopia in all scenarios (numbers are rounded to the nearest tenth).

Crop	**Low fertility variant**				**Medium fertility variant**				**High fertility variant**			
	H	**V-1**	**V-2**	**V-3**	**H**	**V-1**	**V-2**	**V-3**	**H**	**V-1**	**V-2**	**V-3**
Teff (cereals nes)	23.6	21.3	18.9	16.5	25.9	23.3	20.7	18.1	28.3	25.4	22.6	19.8
Maize	41.0	36.9	32.8	28.7	44.9	40.4	36.0	31.5	49.0	44.1	39.2	34.3
Sorghum	28.8	26.0	23.1	20.2	31.6	28.5	25.3	22.1	34.5	31.0	27.6	24.1
Wheat	19.7	17.7	15.7	13.8	21.6	19.4	17.3	15.1	23.5	21.2	18.8	16.5
Barley	16.1	14.5	12.8	11.2	17.6	15.9	14.1	12.3	19.2	17.3	15.4	13.4
Millet	5.5	4.9	4.4	3.8	6.0	5.4	4.8	4.2	6.6	5.9	5.2	4.6
Beans, dry	2.4	2.1	1.9	1.7	2.6	2.4	2.1	1.8	2.9	2.6	2.3	2.0
Chick peas	1.8	1.7	1.5	1.3	2.0	1.8	1.6	1.4	2.2	2.0	1.8	1.5
Broad beans, horse beans, dry	4.3	3.9	3.5	3.0	4.7	4.3	3.8	3.3	5.2	4.6	4.1	3.6
Lentils	0.6	0.5	0.5	0.4	0.6	0.6	0.5	0.4	0.7	0.6	0.6	0.5
Vetches	1.2	1.1	1.0	0.8	1.3	1.2	1.1	0.9	1.4	1.3	1.1	1.0
Peas, dry	2.1	1.9	1.7	1.5	2.3	2.1	1.8	1.6	2.5	2.2	2.0	1.7
Vegetables, fresh nes	1.3	1.1	1.0	0.9	1.4	1.3	1.1	1.0	1.5	1.4	1.2	1.1
Seed cotton	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.2	0.4	0.3	0.3	0.3
Fibre crops nes	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Groundnuts, with shell	0.6	0.6	0.5	0.4	0.7	0.6	0.5	0.5	0.7	0.7	0.6	0.5
Sesame seed	1.8	1.7	1.5	1.3	2.0	1.8	1.6	1.4	2.2	2.0	1.8	1.5
Linseed	1.9	1.7	1.5	1.3	2.1	1.9	1.7	1.5	2.3	2.0	1.8	1.6
Oilseeds nes	3.1	2.8	2.5	2.2	3.4	3.1	2.7	2.4	3.7	3.3	3.0	2.6
Roots and tubers nes	3.8	3.4	3.1	2.7	4.2	3.8	3.3	2.9	4.6	4.1	3.6	3.2
Sweet potatoes	0.9	0.8	0.7	0.6	1.0	0.9	0.8	0.7	1.1	1.0	0.9	0.8
Potatoes	0.6	0.5	0.5	0.4	0.6	0.6	0.5	0.5	0.7	0.6	0.6	0.5
Coffee, green	6.9	6.2	5.5	4.8	7.5	6.8	6.0	5.3	8.2	7.4	6.6	5.8
Chillies and peppers, dry	6.5	5.9	5.2	4.6	7.2	6.4	5.7	5.0	7.8	7.0	6.2	5.5
Total	174.9	157.4	139.9	122.4	191.8	172.6	153.5	134.3	209.2	188.3	167.4	146.4

H: Horizontal scenario, V-1: Vertical scenario-1, V-2: Vertical scenario-2, V-3: Vertical scenario-3

Table B8. Required land areas (in 1000 km^2) of crops by 2050 in Ethiopia in all scenarios (numbers are rounded to the nearest tenth).

Crop	**Low fertility variant**				**Medium fertility variant**				**High fertility variant**			
	H	**V-1**	**V-2**	**V-3**	**H**	**V-1**	**V-2**	**V-3**	**H**	**V-1**	**V-2**	**V-3**
Teff (cereals nes)	58.5	37.3	28.7	23.3	64.2	40.9	31.5	25.6	70.0	44.6	34.3	27.9
Maize	41.9	25.9	19.9	16.2	46.0	28.4	21.8	17.7	50.1	31.0	23.8	19.3
Sorghum	33.8	21.3	16.4	13.3	37.0	23.4	18.0	14.6	40.4	25.5	19.6	16.0
Wheat	30.5	19.0	14.6	11.9	33.5	20.8	16.0	13.0	36.5	22.7	17.5	14.2
Barley	23.0	15.1	11.6	9.4	25.2	16.6	12.7	10.3	27.5	18.1	13.9	11.3
Millet	8.7	5.1	3.9	3.2	9.5	5.6	4.3	3.5	10.4	6.1	4.7	3.8
Beans, dry	5.5	3.3	2.5	2.1	6.1	3.6	2.8	2.3	6.6	3.9	3.0	2.5
Chick peas	4.6	2.7	2.1	1.7	5.1	3.0	2.3	1.9	5.6	3.3	2.5	2.0
Broad beans, horse beans, dry	10.0	6.4	4.9	4.0	11.0	7.0	5.4	4.4	11.9	7.7	5.9	4.8
Lentils	2.0	1.3	1.0	0.8	2.2	1.4	1.1	0.9	2.4	1.5	1.2	0.9
Vetches	2.9	1.8	1.4	1.1	3.2	2.0	1.5	1.3	3.5	2.2	1.7	1.4
Peas, dry	4.9	3.1	2.4	1.9	5.3	3.4	2.6	2.1	5.8	3.7	2.8	2.3
Vegetables, fresh nes	4.1	3.7	2.8	2.3	4.5	4.0	3.1	2.5	4.9	4.4	3.4	2.8
Seed cotton	1.7	1.0	0.8	0.6	1.8	1.1	0.8	0.7	2.0	1.2	0.9	0.7
Fibre crops nes	6.5	6.0	4.6	3.7	7.1	6.5	5.0	4.1	7.8	7.1	5.5	4.5
Groundnuts, with shell	1.0	0.6	0.5	0.4	1.1	0.7	0.5	0.4	1.2	0.8	0.6	0.5
Sesame seed	4.1	2.9	2.2	1.8	4.4	3.1	2.4	2.0	4.8	3.4	2.6	2.1
Linseed	2.8	1.8	1.4	1.1	3.1	2.0	1.5	1.2	3.4	2.2	1.7	1.3
Oilseeds nes	6.2	3.1	2.4	2.0	6.8	3.4	2.6	2.2	7.4	3.8	2.9	2.3
Roots and tubers nes	14.2	13.4	10.3	8.4	15.5	14.7	11.3	9.2	16.9	16.0	12.3	10.0
Sweet potatoes	1.8	1.5	1.2	0.9	2.0	1.7	1.3	1.0	2.2	1.8	1.4	1.1
Potatoes	1.3	0.9	0.7	0.5	1.5	0.9	0.7	0.6	1.6	1.0	0.8	0.6
Coffee, green	9.2	7.1	5.4	4.4	10.0	7.8	6.0	4.8	11.0	8.5	6.5	5.3
Chillies and peppers, dry	1.8	1.5	1.2	1.0	1.9	1.7	1.3	1.1	2.1	1.8	1.4	1.2
Total	280.9	185.7	142.8	116.1	308.0	203.7	156.7	127.3	335.9	222.1	170.8	138.8

H: Horizontal scenario, V-1: Vertical scenario-1, V-2: Vertical scenario-2, V-3: Vertical scenario-3

List of publications

Peer-reviewed journal articles

Ayyad, S., Karimi, P., Ribbe, L., Becker, M., 2024. Potential improvements in crop production in Egypt and implications for future water and land demand. International Journal of Plant Production. https://doi.org/10.1007/s42106-024-00301-7

- Contribution: conceptualization; methodology; formal analysis; writing original draft.

Ayyad, S., Karimi, P., Langensiepen, M., Rebelo, L.-M., Ribbe, L., Becker, M., 2022. Remote sensing assessment of available green water to increase crop production in seasonal floodplain wetlands of sub-Saharan Africa. Agricultural Water Management 269, 107712. https://doi.org/10.1016/j.agwat.2022.107712

- Contribution: conceptualization; methodology; formal analysis; writing original draft.

Ayyad, S., Khalifa, M., 2021. Will the Eastern Nile countries be able to sustain their crop production by 2050? An outlook from water and land perspectives. Science of the Total Environment 775, 145769. https://doi.org/10.1016/j.scitotenv.2021.145769

- Contribution: conceptualization; methodology; formal analysis; writing original draft.

McNamara, I., Baez-Villanueva, O.M., Zomorodian, A., **Ayyad, S.**, Zambrano-Bigiarini, M., Zaroug, M., Mersha, A., Nauditt, A., Mbuliro, M., Wamala, S., Ribbe, L., 2021. How well do gridded precipitation and actual evapotranspiration products represent the key water balance components in the Nile Basin? Journal of Hydrology: Regional Studies 37, 100884. https://doi.org/10.1016/j.ejrh.2021.100884

- Contribution: conceptualization; review & editing.

Conference contributions

Ayyad, S., Karimi, P., Langensiepen, M., Ribbe, L., Rebelo, L.-M., Becker, M., 2023. Exploring the potential of increasing crop production using available green water in sub-Saharan Africa. Oral presentation. Cairo Water Week. Cairo, Egypt, 29 October–02 November 2023.

Ayyad, S., Karimi, P., Langensiepen, M., Ribbe, L., Rebelo, L.-M., Becker, M. Increasing cropping options in seasonal floodplain wetlands of sub-Saharan Africa: A remote-sensing approach for assessing available green water for cultivation. Oral presentation. EGU General Assembly, Vienna, Austria, 23–27 May 2022, https://doi.org/10.5194/egusphere-egu22-3982

Ayyad, S., Khalifa, M. 2021. Sustainability of agricultural systems in the Eastern Nile countries: Trajectories, opportunities, and constraints. Oral presentation. Cairo Water Week. Cairo, Egypt, 24–28 October 2021.

Ayyad, S., Karimi, P., Langensiepen, M., Ribbe, L., Becker, M., 2021. Green water for productive cultivation in seasonal floodplain wetlands in sub-Saharan Africa. Online oral presentation. Delft International Conference on Sociohydrology. Delft, the Netherlands, 06–08 September 2021.

Ayyad, S., Khalifa, M. 2021. Agricultural futures in Egypt, Ethiopia, and Sudan. Online oral presentation. Delft International Conference on Sociohydrology. Delft, the Netherlands, 06–08 September 2021.

Ayyad, S., Khalifa, M. 2021. The water and land demands of the agricultural practices in the Eastern Nile Basin: Current status and future opportunities. Online oral presentation. Nile Basin Development Forum. Virtual event, 09 March–29 April 2021.

Ayyad, S., Khalifa, M. 2021. Unlocking the potential of agricultural productivity and water use efficiency in the Eastern Nile countries. Online oral presentation. Water Security and Climate Change Conference, Hanoi, Vietnam, 01–04 March 2022.