A Triply Green Revolution

Building water resilience for SDGs on food and poverty for Africa

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Abstract
Sub-Saharan Africa is confronted with the urgent challenge of ensuring food security in the face of changing demographics, climate change and water vulnerability, which can lead to potential crop failure. Despite the high advocacy for technological solutions, such as irrigation, rainfed agricultural systems, which account for more than 90% of the region's food production, often remain overlooked. This raises the question of which water sources can be sustainably utilized to meet the Sustainable Development Goals. This thesis investigates the significant role of "green water" in addressing these challenges in agricultural production and ecosystem health in the sub-Saharan African region.

Application of models reveal the pronounced role of green water in African forest systems, regional ecosystems, and food production systems in studying these societal sustainability questions. The study projects a decrease in precipitation recycling with increasing severity of climate change. The results suggest that regions with lower water efficiency per yield production can significantly increase agricultural yield by tapping into green water sources as improving rainwater management systems, even as land-sourced precipitation is projected to decline more than oceanic sources.

The thesis argues for adoption of a green water-centric approach to be opted in strategic plans at both local and global levels. Moreover, by capitalizing on green water resources, less developed nations such as sub-Saharan Africa can fulfill their Sustainable Development Goals without the need for significant technological investments and the associated environmental risks.

Keywords: Sustainable Development Goals SDGs, Africa, water resilience, green-blue water, agriculture, climate change, land-use change, planetary boundaries.

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A TRIPLY GREEN REVOLUTION
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Building water resilience for SDGs on food and poverty for Africa

Maganizo Kruger Nyasulu
To Dad, Philip, and
in Loving memory of
Mum, Grace,
For steadfastly propelling
me to greater heights with
unwavering support.
"Water is the bloodstream of the biosphere"

Malin Falkenmark
Academic Dissertation for the Degree of Doctor of Philosophy in Sustainability Science awarded by Stockholm University

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And in loving memory:
Professor Malin Falkenmark

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Abstract

The global pursuit of the Sustainable Development Goals, such as eradicating hunger and securing sustainable food production by 2030, presents a significant challenge for humanity. This is particularly evident in sub-Saharan Africa, a region grappling with extensive malnutrition, poverty, changes in population demographics, and severe climate conditions that lead to issues of water variability.

My thesis examines the crucial roles of water in agricultural production and ecosystem health and analyses how human livelihood, SDGs, are threatened by future global changes. Using the Lund Potsdam Jena – Managed Land and the Utrecht moisture tracking model, I develop a broad understanding of the factors that impact changes in the water cycle along the way from evaporation to atmospheric moisture to precipitation to soil moisture to crop consumption, now and into the future. This approach permits analysis of the distinct roles of classic 'blue water' (runoff and water stored in water bodies) but also of 'green water' (precipitated water available for plant consumption, and water stored in plant biomass or soil that can be transpired) as a so far neglected and underestimated resource for agriculture.

I focus on mapping the origins of water for African agricultural systems and the important ecosystems that supply water through the water cycle. I analyse these water processes at current levels (Paper I) and how they will change in the future under global changes (Paper II). I extend the global assessments to understand the effects of interactions of the planetary boundaries (PB) for climate change and green water on food security (Paper III). Finally, I assess in modelling way the extent to which the green water potential can increase food production (Paper IV).

A key finding of my research is that green water plays a very pronounced role in African forest systems (Paper I), regional ecosystems (Paper II) and food production systems (Paper I, III and IV). Paper I reveal that agricultural systems in central and western parts of the African continent have a high dependence on terrestrially sourced precipitation water, dominated by the Congo rainforest. Paper II projects a decrease in precipitation recycling with increasing severity of the climate change scenario, with mostly land-sourced precipitation showing a higher decline than oceanic sources. Paper III finds that intensifying anthropogenic climate change adversely affects the status of the green water PB, threatening green water’s ability to support food production. Paper IV assesses that regions with lower water efficiency per yield production can substantially increase agricultural yield by tapping into green water sources and improving rainwater management systems. This follows the premises of a triply green revolution, an approach that underscores the need for sustainable use and management of green water to double food production.
I therefore advocate for a stronger green water-centric approach that acknowledge and champions green water in strategic plans at both local and global levels. With my thesis I also hope to stimulate scientific discussions around the methodologies and results presented, while recognising the embedded limitations. By capitalizing on green water resources, less developed nations like SSA can fulfil their SDG objectives without significant technological investments and the accompanying environmental risks.

**Keywords:** Sustainable Development Goals SDGs, Africa, water resilience, green-blue water, agriculture, climate change, land-use change, planetary boundaries
Sammanfattning

Livsmedelsproduktion till 2030, utgör en av de största utmaningarna mänskligheten har ställts inför. Detta är särskilt påtagligt i vissa regioner, däribland subsahariska Afrika, en region som redan brottas med uttalad undernäring, fattigdom, snabb befolkningsökning och svåra klimatförhållanden som intensifierar problem med vattenvariationer.

Denna avhandling undersöker vattnets betydande roll i jordbruksproduktion och ekosystemhälso samt analyserar hur de Globala målen kopplade till människor försörjning hotas av kommande globala förändringar. Genom användning av Lund Potsdam Jena - Managed Land och Utrecht fuktspårningsmodell utvecklar jag en bred förståelse för de faktorer som har inverkan på förändringar i vattencykeln, från avdunstning till atmosfärisk fuktighet till nederbörd till markfuktighet till grödans konsumtion, nu och även i framtiden. Denna metod möjliggör analys av de distinkta rollerna för klassiskt "blått vatten" (avrinning och vatten lagrat i vattendrag) men också av "grönt vatten" (nederbördsvatten tillgängligt för grödors upptag/konsumtion och vatten lagrat i växtbiomassa eller jord som kan transpireras) som en hittills förbisedd och underskattad källa för jordbruket.


En viktig upptäckt av min forskning är att grönt vatten spelar en betydande roll i afrikanska skogssystem (Artikel I), regionala ekosystem (Artikel II) och livsmedelsproduktionssystem (Artikel III och IV). Artikel I visar att jordbruksystemen i centrala och västra delarna av den afrikanska kontinenten är i högsta grad beroende av nederbördsvatten från land, dominerat av Kongoregnskogen. Artikel II förutspår en minskning av nederbördsväte med ökande allvarlighetsgrad av klimatförändringsscenarier, där mestadels landbaserad nederbörd visar en större nedgång än havbaserade källor. Artikel III konstaterar att intensifierad antropogen klimatförändring har en negativ effekt på statusen för den planetära gränsen för grönt vatten vilket hotar grönt vattens förmåga att stödja livsmedelsproduktionen. Artikel IV illustrerar att regioner med lägre vatteneffektivitet per skördproduktion kan avsevärt öka jordbruksavkastningen genom att utnyttja grönt vatten och effektivisera regnhanteringssystem. Detta följer principerna för en tredubbel grön revolution, en metod som betonar behovet av hållbar användning och förvaltning av grönt vatten med syfte att fördubbla livsmedelsproduktionen.

**Nyckelord:** Globala målen, Afrika, vattenresiliens, grönt-blått vatten, jordbruk, klimatförändringar, förändrad markanvändning, planetära gränser
Tsatanetsatane

Kutsatira ndondomeko za padziko lonse zochedwa Zolinga Zachitukuko Chokhazikika - Sustainable Development Goals (SDG) zomwe zinakhazikitsidwa ndi bungwe la United Nations, monga kuthetsa vuto la njala ndi kupezeku kwa chakudwa chokwaniara pofika muchaka cha 2030, kuli pa chiopwezo komanso kutha kubweretsa vuto lalikulu kwa anthu. Izi nzoonekeratama makamaka umaiko omwe ali chakumwera kwa Africa, dera lomwe lalikululukukuntha kwambiri ndi kupelewerana kwa zakudwa za m'thupi, umphawi, kusinthu kwa chiwerengero cha anthu, komanso kusinthu kwa nyengo komwe kukubweresta vuto la kusintha kwa madzi a mthaka.

Ndemangayi, likuwunika ntchito zofunika kwambiri zokhuza madzi omwe amagwilitsidwa ntchito muzalulikana anthu la chilengedwe komanso ma SDGs okhuza myoyo ya anthu ali pa chiopsisomo kamba ka kusinthu kwa padsiko lonse la pansi. Pogwiritsa ntchito njira ya Lund Potsdama Jena – Managed Land ndi kalondolondo wa chinyezi wotchewa Utrecht model, ndili ndi kumvetetsa kwawino mu nyengo ino komanso mtsogolomu, momwe zinthu zomwe zimakhudza kusintha ndi kusintha kwambiri anthu munjiira yochokera ku nthunzi za mpweya ku chinyezi cha mumnglela nga chomwe chimabweretsa mvula, nkudzabwelerana ku chinyezi cha nthaka mpaka kufulekudza kwa mbewu. Njirayi imalalaula kusinthu ntchito nzikhapanda kapena zosiyasiyana zotchedwa “madzi a bulu” (awa ndi madzi othamanga pamwamba pa nthaka ndi nthaka opeze pa nthaka peni pa nthaka) komanso “madzi obiliwira” (awa ndi madzi amvula omwe amapezeka kuti zomera zigwilite ntchito, ndi madzi osungidwa muzomeramera komanso omwe nthaka imatha kusinthiwa)” nga wera lonyalanyazidwa komanso lophopetsedwa pa pazaulimi.

Ndafufuza kwambiri mba yokhuza madzi a zaulimi wa ku Africa ndi zachilengedwe zofunika zomwe zimapereka madzi kudzera mukuzungulira komwe komwe madzi amayendamo kuti kung’angano madzi. Ndasanthula njira zamadzi zofunika ziyorokhala mu Africa ndi zachilengedwe zofunika zomwe zimapereka madzi kudzera mukuzungulira komwe komwe madzi amayendamo kuti kung’angano madzi. Ndasanthula njira zamadzi zofunika ziyorokhala mu Africa ndi zachilengedwe zofunika zomwe zimapereka madzi kudzera mukuzungulira komwe komwe madzi amayendamo kuti kung’angano madzi.


Chifukwa chake ndimalimbikitsa njira yolimba yamadzi obiriwira yomwe imavomereza ndikuwongolera madzi obiriwira m’mapulani anzeru m’madera onse am’deralo komanso padziko lonse lapansi. Ndi chiphunzitsochi ndikuyembekezanso kulimbikitsa zokambirana za sayansi mozungulira njira ndi zotsatira zomwe zaperekedwa, ndikuzindikira zolephera zomwe zaphatikizidwa. Pogwiritsa ntchito madzi obiriwira, mayiko osatukuka kwambiri monga SSA amatha kukwaniritsa zolinga zawo za SDG popanda ndalama zambiri zamakono komanso zoopsa zomwe zimatsatira chilengedwe.

**Mawu osakira:** Zolinga Zachitukuko Chokhazikika, Africa, ntchito za Madzi, Madzi a obiliwira-buluu, ulimi, kusintha kwanyengo, kusintha kwa kagwiritsidwe ntchito ka nthaka, malire a dziko
List of Papers


   A two-fold analysis of sources of moisture responsible for agricultural production in Africa, and the role of rainforest in supplying water consumed in cropland.


   Mapping future atmospheric moisture flows and availability under changing climatic conditions and land use and land cover change.


   An analysis of green water resilience effect on food production due to climate change and green water planetary boundary interactions.


   An assessment of green water potential to increase food production under different climate scenarios and management practices. It also projects the effective green water (transpiration) trajectory to the end of the century.

*These authors contributed equally to this work

† Deceased

Contributions (using the CrediT author statement guidelines)

**Paper I, III, and IV:** Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing

**Paper II** Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing - review & editing
Additional relevant papers outside the PhD thesis

Manuscript drafts


   Landscape mapping of blue and green water flows and stocks at landscape level over a specified period using a hydroclimatic regime framework.

Policy Briefs


   Policy brief highlighting the crucial roles of forest to water cycles and the likelihood of increased water security on smallholder agroforestry farms in the tropics. It offers opportunities to adopt agroforestry as a landscape restoration practice to make degraded lands more resilient to the consequences of global change.

Anthology Book (published)


   An anthology of futuristic visions of Africa grounded in Nature Futures Framework. The stories are set out to impact a transformative narrative of future of the Kingdom.

Contributions (CRediT)

1. Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing

2. Investigation, Writing - review & editing

3. Writing - review & editing
Glossary

Blue Water: is the sum of surface water (runoff, river flows, etc) and ground deep aquifer recharge.

Climate change: long-term changes in the measures of global atmospheric characteristics over time – including precipitation and temperature.

Evaporation-shed: encompasses the sink regions that receive significant precipitation from a source region under study.

Green Water: generally including all land-to-atmosphere or atmosphere-to-land flows into and out of a hydrologic unit during a period of interest. It is all precipitated water available for plant consumption, and water stored in plant biomass or soil that later can be transpired.

Hydroclimate: conditions that bring together hydrology and climate and are shaped by hydrologic characteristics (on land) and the atmospheric climatic (in the atmosphere) conditions.

Hydroclimatic unit: a bounded unit of Earth’s land surface, of any size or shape, which is free to receive inflow from either the atmosphere as precipitation or from upgradient hydrologic units as landscape (groundwater and surface-water) inflow.

Hydroclimatic Regime: as the particular combination of green- and blue-water-balance components that characterizes the baseline functioning of a particular hydrologic unit (of any size) averaged over a specific time step of interest (of any length).

Land-use change: a process by which human activities permanently transform the natural landscape, but also referring to how the land is used, usually emphasizing the functional role of land for economic activities.

Moisture recycling: the process of evaporation from a source region, traveling through the atmosphere as vapor, and returning to the downwind area as precipitation.

Precipitation-shed: encompasses the source regions that contribute significantly to the precipitation in the evaporation-shed.

Resilience: the capacity of a system to absorb perturbations without losing its basic functionality.
# Contents

1 Introduction .................................................................................................................. 1

2 Background .................................................................................................................. 4
   2.1 Water and Sustainable Development Goals ...................................................... 4
   2.2 Global Sustainability and Sub-Saharan Africa .................................................. 5

3 Aim and Scope of the Thesis ....................................................................................... 6

4 Key concepts and theoretical approaches ................................................................... 9
   4.1 Water Resilience ................................................................................................. 9
   4.2 Moisture Recycling ............................................................................................. 10
   4.3 A Blue and Green water perspective .................................................................. 11
   4.4 Hydroclimatic Regimes .................................................................................... 12
   4.5 Planetary Boundaries ....................................................................................... 13
   4.6 Triply Green Revolution ................................................................................... 15

5 Methodology ................................................................................................................ 16
   5.1 Modelling for water resilience ......................................................................... 16
   5.2 Simulation set-up ............................................................................................... 17
   5.3 Limitations ......................................................................................................... 18

6 Summaries of the thesis papers ................................................................................... 19
   6.1 Paper I - Rainforests feed Sub-Saharan Africa ............................................... 20
   6.2 Paper II - Climate and land use change decrease future moisture feedback .... 21
   6.3 Paper III – Rainfed agriculture is at risk of green water boundary transgression. 22
   6.4 Paper IV – Green water potential to support achievement of SDGs .............. 24

7 Insights and Contributions ............................................................................................ 26
   7.1 Improved methods and approaches for assessing green water status .......... 26
   7.2 Analytic insights about changing drivers of water change: Land-Atmosphere interactions for water and agriculture assessments ..................... 27
   7.3 Conceptual advances on water resilience and changing sustainability risks ........ 28
   7.4 Science-informed advocacy for a triply green revolution for sustainable food 29

8 Conclusions and Outlook ............................................................................................. 30

Epilogue ......................................................................................................................... 33

Acknowledgments ......................................................................................................... 35
Introduction

"When a man is at peace with his gods and ancestors, his harvest will be good or bad according to the strength of his arm."
– Chinua Achebe, Things Fall Apart

Water, the living environment and human societies can be understood as a strongly intertwined system. Water serves as the ‘blood stream’ for human well-being and socio-economic development (social systems), and the environment (ecological systems). Throughout the water cycle from evapotranspiration to atmospheric moisture transport to precipitation to soil moisture to plant uptake, water connects different regions and elements of the Earth system (the ocean, the land, the atmosphere, and the biosphere). Management of water resources has been an indispensable element throughout history. It remains responsible for ‘providing’ food, fuel and fibre, regulating the environment, and as a cultural symbol embedded in aesthetics and spirituality across civilizations (Falkenmark et al., 2019; McCool et al., 2008).

Hence, water is an ‘agent’ of change, ensuring that ecosystems and the services it provide for humanity are resilient towards shocks and long-term global changes. These roles that water plays to ensure the functioning of other sectors are regarded as water resilience (Rockström et al., 2014). But regionally, water equally is increasingly becoming a scarce resource, compromising social and environmental benefits attained from its provisioning, regulating, cultural, and ecosystem services (Gleeson et al., 2020). Regional depletion has made water become a ‘victim’ of anthropogenic impacts, both directly by human overuse (e.g. for drinking water, agriculture, and industry), or indirectly by land use change, alteration of landscapes and deforestation (Albert et al., 2021; Kummu et al., 2016; Wada and Bierkens, 2014).

Regional depletions and global changes compromise the progress towards attaining the internationally agreed Sustainable Development Goals (SDGs) (UN, 2015). The SDGs can be regarded as societal and environmental minimum requirements to be achieved for any society to ensure thriving human-nature relations. Of particular interest is sub-Saharan Africa (SSA) where high levels of demographic change are expected (UN, Department of Economic and Social Affairs, Population Division, 2022) and already today high levels of poverty, malnourishment, and climate driven water stress threaten the region’s progress towards achieving the SDGs (FAO, 2020; Keys and Falkenmark, 2018). Agricultural production is a key component for livelihood; food security and economic wellbeing (Scoones, 2013, 1998). Yet globally, agriculture accounts for ~70% of freshwater use (Ingrao et al., 2023; Rockström et al., 2010). The interplay of land use, water use, climate change and social development trends raises questions as to whether there will be enough freshwater of sufficient quality to produce food to ensure basic human well-being.
Freshwater can be partitioned into visible blue water and invisible green water (Falkenmark and Rockström, 2006), informally referred to as ‘streaming’ and ‘steaming’ water. **Blue water** is water partitioned into runoff (either through streams, soil flow, rivers, or lakes) or infiltrated into bedrock as groundwater (Falkenmark, 1986). In contrast, **green water** is the invisible part of the water cycle (Falkenmark and Rockström, 2006). Green water includes all precipitated water available for plant consumption, and water stored in plant biomass or soil that later can be transpired (Falkenmark, 1986; Falkenmark and Rockström, 2006).

Global estimates suggest that while only ~1,700 to ~2,600 km$^3$/year of blue water is available to agricultural systems, the ~3,600 to ~5,000 km$^3$/year of green water is more than twice greater and should also be considered as a resource (Destouni et al., 2013; Falkenmark and Rockström, 2006; Qin et al., 2019). Traditionally only the visible blue water has been taken to be the available resource, to the extent that it is explicitly addressed in SDG target 6.4 ‘ensuring adequate blue water resources for humans and ecosystems’ (Jaramillo et al., 2019; Kummu et al., 2016; UN, 2015). Although green water has not attracted much attention yet, it has been recognized to contain a big potential for supporting sustainable development (Falkenmark and Rockström, 2006).

As the global demographic changes to increase rapidly, so does the demand for food. However, food production is not an isolated process; it’s directly tied to water use (Gerten, 2013). To meet the projected global food demand, agricultural production must increase by 70% by 2050 (Huang et al., 2019; Rost et al., 2008; Wada and Bierkens, 2014). This increase in food production implies a corresponding surge in water use. But the relationship between food production and water use is not always linear (Vadez et al., 2023). The efficiency of water use in agriculture plays a pivotal role in determining the actual water demand (Njiraini et al., 2016). Efficient water use in agriculture is crucial to ensure that the increased food production does not lead to unsustainable water use. This is particularly relevant as most of the food production is expected to occur in today’s developing nations (Alexandratos and Bruinsma, 2012; Godfray et al., 2010). Therefore, intensifying food production to meet this demand, without considering water use efficiency, could potentially lead to overexploitation of water resources, posing significant environmental challenges (Campbell et al., 2017; Ramankutty et al., 2018).

In response to these escalating global environmental risks, Rockström et al., (2009) introduced the Planetary Boundaries (PB) conceptual framework. This framework was set out from the beginning as a scientific initiative that aims to consolidate the effects of human activities and the loss of Earth system resilience. The framework encompasses nine boundaries (Rockström et al., 2009; Steffen et al., 2015; Richardson et al., 2023), and of recent, the freshwater boundary has been revised to include green water (Wang-Erlandsson et al., 2022). The PB framework is designed to delineate a ‘safe operating space for humanity’, preventing unacceptable changes in Earth’s life-support systems and sustaining a state that is beneficial for human existence (Rockström et al., 2009; Steffen et al., 2018, 2015) (for more detail refer to section 4.5). Current results indicate that six out of nine boundaries have already been transgressed (Richardson et al., 2023).
Therefore, I aim to understand the roles that water plays in maintaining the future resilience of Earth’s biogeoophysical system and human livelihoods. I explore the intricate connections between these two systems, taking the SDGs as a benchmark of human livelihood and ecosystem health at sub-global scales. The PB framework provides a basis for describing Earth system stability and resilience.

I examine the interlinkages between ecosystems and human society as social-ecological systems, with a focus on water resilience for both humans and nature (for more detail refer to section 4.6). In this context, the concept of the ‘triple green revolution’ becomes particularly relevant (Falkenmark and Rockström, 2004). This concept advocates for the sustainable use and management of green water with the goal of increasing food production (for more detail refer to section 4.7).
2 Background

“In nature nothing exists alone”
– Rachel Carson, Silent Spring

2.1 Water and Sustainable Development Goals

Representing water from a social-ecological systems perspective is grounded on the understanding that tight non-linear connections and feedback cycles exist between the social and ecological entities (Rockström et al., 2014). To illustrate, moisture sourced from rainforest evapotranspiration rains locally or is transported across distances to agricultural lands where it precipitates, enabling the production of food, fibre and timber (Nyasulu et al., 2024). The provision of precipitation to produce these products of food and fibre, support local societies and enables actions for achieving SDGs on ‘Poverty Alleviation’ (SDG 1) and ‘Hunger Eradication’ (SDG 2). The achievement of these SDGs ensures a positive livelihood driven by SDG 3 (‘Good Health’), also supporting healthy ecosystems (SDG15 ‘Life on land’).

Water from precipitation is only partly complemented with moisture from non-terrestrial sources like oceans but is also strongly maintained by terrestrial sources like (rain)forests, wetlands, and open water bodies (lakes and rivers) which are equally connected to this cyclic system (see Fig. 1). The water cycle is complex, and environmental changes can have quite drastic consequences for local water cycle and, thus, crop production. For instance, agriculture expansion into rainforest can reduce moisture flow from rainforests which ultimately affects the viability of agricultural production (Lenton et al., 2008; Wunderling et al., 2022; Xu et al., 2022). A reduction in soil moisture can deflect moisture availability for plants and evaporation. This moisture drop impacts the soil’s capacity to hold below-ground carbon triggering carbon release into the atmosphere and contributing to climate warming (Humphrey et al., 2018). Due to humanity’s impact on the environment through climate change and land use alterations, the challenge of maintaining the Earth’s system stability is escalating, leading to a resilience loss of the social-ecological system. Nevertheless, water functions hold the key to mediate this loss in resilience (Falkenmark et al., 2019).

Since the adoption of the seventeen SDGs in 2015, there has been a noticeable increase in conflicts between environmental goals (SDG13 ‘Climate Action’; SDG14 ‘Life Below Water’; and SDG15 ‘Life on Land’) and the other 14 socio-economic goals. Achieving both - ensuring socio-economic standards for everybody while respecting environmental limits - seems an extraordinary task (Collste et al., 2021; Randers et al., 2019). Since their adoption, there has been a growing demand for a systemic approach to understanding the interactions of SDGs (Griggs et al., 2017; van Soest et al., 2019). The approaches used involve integrating and paying attention to the interactions and interrelationships between the socio-economic goals and the environmental factors that influence them (Pedercini et al., 2019; van Soest et al., 2019). This approach that is more comprehensive than isolating individual parts, embodies the principles of systems thinking, where all essential parts need to be included (Meadows, 2008).
2.2 Global Sustainability and Sub-Saharan Africa

Despite substantial progress in addressing actions on climate mitigation, and hunger eradication in SSA, the region remains characterized by the highest per capita rates of poverty, nutritional deficiencies, and water scarcity (FAO, 2020). Projections indicate that these challenges will intensify in the face of future climate change and growing changes in demographics (Bhattacharyya et al., 2020; FAO, 2021). Despite advances in formal employment towards off-farm jobs, there is still heavy reliance on smallholder farming for food self-sufficiency, but also to employ the region’s workforce (Jayne et al., 2017). SSA landscapes, primarily savannas, often face water deficiency due to local evaporation exceeding precipitation, which challenges on-farm water productivity (Bunting et al., 2018; Synodinos et al., 2018). Consequently, it is crucial for smallholder farmers to have a comprehensive understanding of the origins of rainfall, its current and future availability, as well as adaptive management strategies. This knowledge equips farmers with a range of on-farm water management options, reducing the risk of income loss from crop failure, increasing on-farm employment benefits, and alleviating food insecurities that heighten the susceptibility to poverty (Apio et al., 2023; Khatri et al., 2023).

There is evidence that Africa has made progress towards achieving the SDGs despite experiencing significant challenges (Otekunrin et al., 2019; Sachs et al., 2022). However, at a national scale the numbers vary, with SSA lagging far behind most of the Northern African countries. The shock of COVID-19 derailed many SDG advancements across the continent (Modi, 2019; Otekunrin et al., 2020; World Health Organization, 2021). The 2022 SDG Report (Sachs et al., 2022) shows stagnation in SDGs 1, 2 and 3 for SSA, although the region is on track for climate action (SDG 13) despite facing challenges. Sachs et al. (2022) estimated that about 40% of all Africans remain in extreme poverty, and hunger eradication remains a major challenge across the continent.
Aim and Scope of the Thesis

The objective of this thesis is to provide insights on water resilience for sustainable agricultural production, with a particular focus on sub-Saharan Africa.

The thesis aims to address the challenge of assessing the water required to meet food production and ecosystem health by drawing on lessons from natural science, social science, and humanities. This approach is a fundamental principle within Sustainability Science (Apetrei et al., 2021; Clark, 2007; Miller et al., 2014).

Four pressing scientific and societal challenges on the roles of water for social-ecological systems’ resilience in SSA, and the associated research questions are:

**Water resource status:** Because it is important to know at which point water is an agent, a victim and provider of services through the water cycle, I ask: Where is water an 'agent' of change on which people depend? What types of water ('blue and green') is important for African agricultural production? Where are the sources, and to what extent does each source supply water for agriculture? ([Paper I](#))

**Drivers of water change:** Because water functions can be compromised by changes to the Earth’s system, I ask: To what extent is water a 'victim' of global changes arising from climate change and land use change? What is the future pattern of atmospheric moisture provision and feedback? ([Paper II](#))

**Resilience loss:** Because humanity continues to impact Earth’s stability and the water cycle, I ask: Do transgressions of the PBs for green water and climate change impact green water provision services to food production? What are the synergies and trade-offs in strategies to secure green water for food while building water resilience within PBs? ([Paper III](#))

**Potential of green water for food:** Because there is a knowledge gap relating to the potential role of green water for food production, I ask: To what extent does green water have the potential to attain the SDG on food (SDG2) and improve livelihood? And what are plausible green water management strategies? ([Paper IV](#))
This thesis examines water resilience as the ability of water to perform different functions, including sustaining food production and supporting food production and societal livelihoods, sustaining ecosystem services, and replenishing terrestrial water systems through atmospheric (rainfall) and root moisture feedback. To achieve the SDGs on food, building water resilience requires both mitigation and adaptation approaches to sustainable water management. As previously stated, agriculture in SSA relies heavily on the use of green water, primarily in the form of precipitation. Therefore, it can be inferred that enhancing green water management contributes to the improvement of the ‘safe operating space’. This is defined in terms of providing social foundations for societal prosperity while staying within the planetary boundaries that maintain the function of the Earth system.

Understanding this water potential and informing management for water resilience requires examining the current and projected status of water (Papers I and II) and assessing which water characteristics (blue or green water) can play such roles sustainably without compromising social and environmental conditions (Paper III). My research also aims to consider the implications of this green water potential for meeting social needs (SDG2) in the face of resilience loss due to overshoot of multiple PBs, captured by the climate change and green water control variables (Paper III). Papers I and IV are analysed from an African regional perspective, and Papers II and III from a global perspective, taking into account regional implications (see Section 6 for more details).

Achieving food security is a prerequisite for achieving SDG 1, on poverty, and SDG 2, on the eradication of hunger and malnutrition. Achieving these global goals requires a spatially explicit understanding of the water sources and flows that support agriculture. I therefore set out to build a biogeophysical understanding of water and its interactions with landscapes, society and the atmosphere, based on the idea that a deeper understanding can support sustainable livelihoods based on food production and natural resource management choices.

Unlike the potential of blue water for agriculture, which is well known, there is a lack of in-depth understanding of the potential of green water (Schyns et al., 2019, 2015). Both blue and green water support agricultural production, and yet human actions are affecting water availability and its multiple roles in global ecosystems, leading to a loss of water resilience from a PB perspective and jeopardising the achievement of the SDGs. The triply green revolution interventions can help build green water resilience, but it need to be informed by a scientific understanding of the interlinkages between water, agricultural, forests, landscapes, climate change and society (see Fig. 1). These linkages are best analysed using social-ecological systems perspectives.
Figure 1. Cyclic linkages of water to the biosphere and society. The water cycle provides both blue and green water for agricultural production. Blue water is visible, so it is easy to analyse its potential in agriculture production compared to invisible green water. Agricultural production supports achievement of SDGs which are socially safe operating spaces (in this thesis). Society impacts water and climate change, leading to pressures on planetary boundaries and loss of resilience. To build green water resilience in food production, a triply green revolution approach can be used.
4 Key concepts and theoretical approaches

“The power of a theory is exactly proportional to the diversity of situations it can explain.”
— Elinor Östrom.
Governing the Commons: The Evolution of Institutions for Collective Action

4.1 Water Resilience

Water resilience is the role that water plays in building the resilience of other systems, particularly sustaining the prosperity of social-ecological systems (Rockström et al., 2014). Water plays a critical role as a 'provider' of key ecosystem services (food production), and as an 'agent' of change driving changes in other systems (e.g., ensuring environmental flow requirements are met), but it is also a 'victim' of social-ecological change, for example being impacted by moisture feedback decline due to deforestation (Falkenmark et al., 2019; Rockström et al., 2014). These water flow functions are cyclical and non-linear and can exist simultaneously and interact dynamically (Falkenmark et al., 2019).

Resilience is the capacity of a system to absorb disturbance and reorganise while undergoing change, so that it still retains essentially the same function, structure, feedback, and therefore identity (Folke, 2016; Walker and Salt, 2012). Erosion of resilience can be identified when changes from long periods of stable conditions are overtaken by abrupt and random change, mostly presented when thresholds are crossed by critical transitions from one stable state to another (Rockström et al., 2009; Scheffer and Carpenter, 2003). For example, current estimates based on gross primary productivity suggest that about 29% of terrestrial ecosystems and ~24% of marine ecosystems worldwide show symptoms of resilience loss (Rocha, 2022).

At the core of my research is the scientific challenge of understanding the biogeophysical systems that link water, land use, atmospheric composition, and moisture circulation, to better design social- and environmental policies that result in more sustainable and resilient socio-ecological systems. Social-ecological systems and resilience research concepts underpin my biogeophysical research activities. I use social-ecological concepts because they are built around the idea that humans and nature are embedded within the biosphere and together form the foundation of life in the biosphere (Berkes and Folke, 1998; Folke, 2016). Nature provides life-sustaining services such as food, clean water, and breathable air, while conversely, humans are pressed with ensuring that the services provided by biodiversity and well-functioning ecosystems are sustained through sustainable use, conservation, and governance (Reyers et al., 2013). I therefore adopt a social-ecological systems approach to offer a conceptual basis for analysing the intertwined social and environmental systems that underpin sustainable development (see Fig. 1).
Loss of resilience can be manifested by the transgression of PBs away from the safe operating space (green area in Fig. 4) of the green PB (Rockström et al., 2009). Resilience loss is defined here in more biogeophysical terms but with social implications. I have interrogated this resilience loss by embedding it in a social operating space, as demonstrated by the failure or inability to meet core sustainable livelihood needs that are derived from water, as summarized in SDG2, on doubling food production by 2030 (UN, 2015).

4.2 Moisture Recycling

A large body of work has highlighted the crucial links between land-use and the recycling of water vapor from one place to another, a process referred to as ‘moisture recycling’ (Bagley et al., 2012; Savenije, 1995; van der Ent et al., 2010). Most of the interacting processes are complex and non-linear (Fig. 2). Evaporation from ocean and surface source, and evapotranspiration from terrestrial ecosystems is transported into the atmosphere where it either condenses to precipitate locally or is transported downwind before falling as rain elsewhere. Precipitation is intercepted in plant canopies, infiltrates into soils, and contributes to run-off for river and groundwater recharge. Precipitation falling over regions of agricultural land provides water for crop plant growth. Agricultural and land-use decisions have a significant impact on the amount of water that flows into and out of the atmosphere.

The analysis of moisture recycling involved tracking moisture from its region of evaporation to its subsequent downwind atmospheric and land/ocean surface region of precipitation, known as the ‘evaporation-shed’ (van der Ent et al., 2014; Wang-Erlandsson et al., 2014). Similarly, tracing precipitation backwards from its sink location to the upwind land and ocean source region is referred to as the ‘precipitation-shed’ (Keys et al., 2012). Here we can have two perspectives: As illustrated in Fig.2, if we are standing in the agricultural land, we can say the region’s precipitation-shed is located in the rainforest and ocean. Similarly, if we are standing in either the rainforest or ocean, we can say that our location is in the evaporation-shed for agriculture in the distant landscape.

Moisture recycling is an ecosystem service regulated by vegetation and has the potential to significantly impact freshwater partitioning in important ways. Changes to vegetation, such as those caused by rainforest deforestation, can significantly impact freshwater partitioning. Deforestation impacts can be seen in changes to distant rainfall, soil moisture fluctuations, the productivity of distant landscapes (e.g. crop production), and the amount of water that flows into rivers and lakes (i.e. blue water flows). Moisture recycling-related changes have significant and widespread implications, impacting local weather patterns as well as global climate systems (Goodman and Herold, 2014).
Figure 2. Schematic flow of the water cycle. Water moves as evaporation from ocean, land and vegetation into atmosphere driven by sun energy. Some of the water parcels condenses and precipitate locally. Some are transported to distance agricultural land where they precipitate supporting the plants and ecosystems there. Moisture tracking is the process of following these water parcels from source to sink or backwards from the sink to where they are sources is moisture. Precipitation-shed is the upwind atmosphere and surface (here ocean and rainforest) that contributes evaporation to a specific location’s precipitation (here agriculture land). Evaporation-shed is the agricultural land receiving precipitation from ocean and rainforest.

4.3 A Blue and Green water perspective

Analysing water from a blue and green perspective allows for a better approach to answering how water resource management can support sustainable agricultural production, especially in parts of the world like SSA, where green water plays a vital role due to the region’s reliance on rainfed agriculture (Falkenmark and Rockström, 2006). Despite the vital role of green water, most grand scale interventions advocated for water for agriculture have been for blue water (Molden, 2013). One such project was the ‘green revolution’. A movement to increase food crop production characterized by the use of high-yielding crop varieties supported by irrigation systems (blue water), initiated during the 1940s–60s (Mazoyer and Roudart, 2006). The ‘green revolution’ was successful in many parts of the world uplifting agricultural systems in East and Southeast Asia and Latin America, but it failed to achieve its promise in SSA (Evenson, 2003). This experience calls for a different approach that can meet the food production deficit of SSA.
The outlook today is that in many parts of the world, freshwater resources are partitioned more towards social demands rather than which is required for ecosystem resilience (Falkenmark et al., 2019; Gleeson et al., 2020). Furthermore, most efforts look only at the visible blue water systems like run-off and water bodies, limiting the understanding of invisible and yet important green water that is held and transported through plants and soil root-zones (Singh et al., 2020). Looking at both blue and green water redirects the perception towards which water characteristics are vital for which functions in building the resilience of social-ecological systems (Plummer and Baird, 2021).

4.4 Hydroclimatic Regimes

In my thesis, I have used the hydroclimatic regime conceptual framework (Fig. 3) developed by Weiskel et al. (2014, and 2007). The hydroclimatic regime framework is grounded in the categorization of landscape units based on dominant water flows. This categorization distinguishes between four general water regime types, each representing different combinations of vertical and horizontal inflows and outflows within a landscape unit:

- **Green water source**: where precipitation onto the landscape is the principal source for outflows of surface water and groundwater;
- **Green water sink**: where precipitation and evaporation are so balanced that there is minimal surface water and groundwater outflow;
- **Blue water source**: where precipitation and evaporation have minimal effect on inflows and outflows of surface water runoff and groundwater; and
- **Blue water sink**: where almost all surface water and groundwater inflows become evaporative outflows.

This typology enables the categorization of different landscapes, giving clarity about the hydroclimatic realities of different types of agriculture and allowing for assessment of what water and crop management options are appropriate for meeting food security goals in different landscapes.

This classification allows to reveal regions that are essentially green water dominated systems, where precipitation and evaporation constitute the dominant hydrological input and output. It is particularly relevant for food-producing regions in sub-Saharan Africa, which exist in the ‘pure green’ domain, where the little precipitation that falls on the land departs almost entirely as evaporation. In SSA, development activities for reducing hunger and poverty must focus on maximizing the productive use of soil water, keeping in mind the limited availability of blue water resources.
Figure 3. Categorization of hydroclimatic regime landscapes based on (Weiskel et al., 2014), a framework that classifies landscapes based on dominating characteristics of inflow and outflow of precipitation, evaporation, surface runoff and ground water recharges. The four vertices in the precipitation inflow against evaporation outflow plot are represented with examples.

### 4.5 Planetary Boundaries

The PBs framework (Richardson et al., 2023; Rockström et al., 2009; Steffen et al., 2015) represents a synthesis of scientific evidence that human-caused changes to Earth system processes can result in crossing thresholds and entering conditions of large-scale, abrupt or irreversible changes. For some processes, the drivers and changes operate at large-region or global scale (namely, climate change, ocean acidification, ozone layer depletion), while others operate at a more local scale leading on aggregate to ‘slow’ systemic changes in Earth’s biophysical processes (namely, altered nitrogen and phosphorus flows, loss of biosphere integrity, land use change, atmospheric aerosol loading, release of chemical pollution and other novel entities, and freshwater use).
In my thesis, the PB framework has been applied as an estimate of the safe operating space for humanity in the context of green water. This safe operating space is illustrated as the green area in Fig. 4. Moving away from the green area (transgressing the boundaries) compromises the Earth system’s stable functioning and is understood as a loss of resilience (Rockström et al., 2009). The underlying Earth system linkages among the PBs entail that humanity’s pressure on one PB will inevitably impact other PBs (Rockström et al., 2009). Regardless, the PBs have mostly been studied and applied in isolation due to the complexity in analysing and predicting these interactions. I build on (Lade et al., 2020) definition of PB interactions from a systems approach, accounting for the connectivity and co-dependence of the boundaries. Consequently, human-induced changes in one boundary can lead to alterations in another boundary, thereby reshaping the safe operating and risk spaces (Lade et al., 2020; Rockström et al., 2009).

Specific ‘control variables’, are used to measure and assess the extent of human impact on particular PBs. Climate change control variables are the annual average atmospheric carbon dioxide (CO\textsubscript{2}) concentration, set at 350 ppm CO\textsubscript{2}, and the change in radiative forcing, set at 1 W m\textsuperscript{-2} (Richardson et al., 2023). The control variable for the green water boundary is the percentage of annual global ice-free land area with deviations in root-zone soil moisture from the preindustrial variability (Wang-Erlandsson et al., 2022). Current and future projections of freshwater demand to meet humanity’s needs show that the safe operating space of freshwater is already more than committed to human demand, and further transgressed the boundaries of green and blue water (Porkka et al., 2024a; Richardson et al., 2023; Wang-Erlandsson et al., 2022).

**Figure 4.** (a) Illustration of green water planetary boundary showing how water resilience is lost, because of human-caused pressures on the boundary, which has moved it out from the ‘safe operating space’ (shown in green), past the solid black line into the orange zone of rising risks. (b) Showing the part of freshwater sub-boundaries blue-green water PB which is zoomed out in (a) in comparison with all other PB based on Richardson et al., (2023).
The consequences of transgressing the green water PB like any other PBs is that green water loses resilience towards disturbances, with risk of losing its current functionality (e.g. resulting in massive changes of global water cycle and, thus, local water provision) (section 4.1). To this end the scientific challenge is on building water resilience while navigating these zones of increasing risk and uncertainty. Therefore, using the PB framework provides insights on the pressure exerted on water resources, while society advances to double food production beyond 2050 (Lade et al., 2020; Steffen et al., 2015). Understanding these transitions is vital for policy action as they are unpredictable and can pose an excessive cost on society's wellbeing especially in regions that are heavily green water dependent for their food production like SSA (Griggs et al., 2017; Lade et al., 2020; Pedercini et al., 2019). One such key policy alignment is achieving the SDGs.

**4.6 Triply Green Revolution**

A triply green revolution entails the use of green water to double the agricultural production, as required by estimates from UN (2015) to meet future food demand, while utilising sustainable water management in agriculture (Falkenmark and Rockström, 2004). Although this is an attractive concept, there have been few attempts to apply this approach in practice or analyse it at global scale. One example is presented by Rockström and Karlberg, (2010), who proposed that a triply green revolution could be the answer of ‘a quadruple squeeze—from population and development pressures, the anthropogenic climate crisis, the anthropogenic ecosystem crisis, and the risk of deleterious tipping points in the Earth system’. However, model-based analysis shows that current agricultural systems are not well designed to deliver such a triply green revolution either from ecological or conventional agriculture (Campbell et al., 2017; Ramankutty et al., 2018). There remains a gap in modelling studies that tried to understand the level at which triply green transformations can be achieved in regions like SSA.

Understanding current and future changes in green-blue water availability for agriculture for the African continent is vital to inform where and when potential problems will manifest, and what management practices can be adopted to mitigate the problems or prevent catastrophic lock-ins like droughts and crop failure (Falkenmark et al., 2019; Fraser et al., 2013).

Taken together, the concepts outlined here provide a theoretical basis for studying the key challenges. However, applying these mechanistic approaches and other global sustainability concepts while studying regions like sub-Saharan Africa requires caution. The region has a history of colonialism, and it continues to face international marginalization, and high incidences of social and economic inequality. As such, I have applied a critical perspective while engaging with these concepts and their underlining interpretations in sustainability science research. By studying them separately and in combination, they can help to unravel power dynamics and open up conversations about scientific and societal transformation.
5 Methodology

"Everything we think we know about the world is a model. Our models do have a strong congruence with the world. Our models fall far short of representing the real world fully."
— Donella H. Meadows, Thinking in Systems: A Primer

5.1 Modelling for water resilience

Climate change and land use change drive changes in water systems and impact water resilience for agricultural production (Rockström and Karlberg, 2010). To understand current and future directions of these global changes, models allow flexibility in forcing specific climate change, socio-economic and water management scenarios that can propagate different future directions of water resilience. Moreover, approaching complexities of social-ecological systems demands approaches from multiple methodologies (Miller et al., 2014). I use computer-based models as a methodological approach to analysing cause/effect relationships and recurrent patterns within social-ecological systems. In general, models are invaluable tools that generate quantifiable metrics and allow simulation of complex interactions, integrating several factors such as climate, land use, and ecosystem dynamics (McGuffie and Henderson-Sellers, 2014).

As my thesis focuses on water resilience in social-ecological systems, I have used models that allow me to investigate specific parts of the system in light of the concepts and frameworks described in the previous section. Two models have been used throughout the thesis:

- The global dynamic vegetation model LPJmL (Lund Potsdam Jena – Managed Land), version 5.8 (Schaphoff et al., 2018b, 2018a). The LPJmL model was used to dynamically determine distribution and composition of natural vegetation, and also production of rainfed crops with associated carbon-, nitrogen-, and water fluxes, consisting of evaporative and precipitable flows. Furthermore, LPJmL facilitates the development of agricultural management scenarios, enabling the implementation of various strategies targeting green water. This functionality is instrumental in understanding the impact of different management scenarios on food production.

- The Utrecht moisture tracking model UTRACK, which is a Lagrangian atmospheric moisture tracking model (Tuinenburg et al., 2020; Tuinenburg and Staal, 2020). When used in forward tracking mode, it tracks water budgets, allowing for estimating precipitation from source-, where water from evapotranspiration goes into the atmosphere, to potential downwind sink regions, where this water precipitates again to the ground. Applied in reverse mode, also called backward tracking, UTRACK allows tracking any moisture that has come down as precipitation in any region of a sink to the upwind location where is has been evaporated.
Both these models require climate data inputs, generated from global climate simulations by General Circulation Models (GCMs). I use scenarios recommended by the Intergovernmental Panel on Climate Change (IPCC) taking different ‘Representative Concentration Pathways’ (RCPs) for the development over time of greenhouse gas concentrations, combined with different ‘Shared Socioeconomic Pathways’ (SSPs) (IPCC, 2021, 2014; Moss et al., 2010; Riahi et al., 2017; Van Vuuren et al., 2011). The SSPs reflect alternative choices made by the world’s societies, which generate different greenhouse gas emission trends: SSP1: ‘Sustainability'; SSP2: 'Middle of the Road'; SSP3: 'Regional Rivalry'; SSP4: 'Inequality'; and SSP5: ‘Fossil-fueled Development’. In my thesis, different papers have used different forcing data selected to best answer the research questions under investigation (see table 1 for summary).

Table 1. Summary of methods and conceptual frameworks guiding the analysis of the papers in my thesis.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Scale</th>
<th>Timeline &amp; Scenarios</th>
<th>Models used</th>
<th>Conceptual Framework</th>
<th>Climate Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Africa</td>
<td>Current 2008 - 2017</td>
<td>UTRACK &amp; LPJmL</td>
<td>Moisture recycling; Water resilience; blue-green water</td>
<td>ERA5 &amp; GSWP3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2015 - 2100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Global</td>
<td>SSP1-2.6, 2-4.5, 3-7.0, &amp; 5-8.5</td>
<td>UTRACK</td>
<td>Moisture recycling, Water resilience</td>
<td>NorESM2 &amp; CLM5</td>
</tr>
<tr>
<td>III</td>
<td>Global</td>
<td>2000 - 2100 RCP 7.0</td>
<td>LPJmL</td>
<td>PBs; blue-green water; Water resilience</td>
<td>Ensemble of ISIMIP3b protocol (CanESM5, CNRM-CM6-1, CNRM-ESM2-1, EC-Earth3, MIROC6)</td>
</tr>
<tr>
<td>IV</td>
<td>Africa</td>
<td>1985 - 2100 RCP 2.6 &amp; 6.0</td>
<td>LPJmL</td>
<td>Hydroclimatic regime; triply green revolution; Water resilience;</td>
<td>ISIMIP2b HadGEM2-ES</td>
</tr>
</tbody>
</table>

5.2 Simulation set-up

**Paper I:** I used a combination of UTRACK and LPJmL to track moisture flow and analyse plant growth water consumption. I forced both models with same climate data from a combination of fifth generation reanalysis for global climate and weather (ERA5, from the European Centre for Medium-Range Weather Forecasts – ECMWF) and daily Global Soil Wetness Project Phase 3 (GSWP3) data (ECMWF, 2017; Hersbach et al., 2019; Kim and Oki, 2015). LPJmL was used to model the hydrological cycle at surface level, and the feedback of the water cycle on plant growth. The UTRACK model was used to track moisture flows, both forward tracking from rainforest to agricultural land and backward tracking by mapping all moisture sources that fall on agricultural land.

**Paper II:** To explore how, where and how much terrestrial moisture recycling may change with future climate and land use changes, I used the UTRACK model forced with climate data output from the Norwegian Earth System Model version 2 (NorESM2), under tier I of the Coupled Model Intercomparison Project, CMIP6 (Eyring et al., 2016). The NorESM2 output data was simulated with land use input data from Community Land Model (CLM 5) scenario datasets based on CMIP6 SSPs (IPCC, 2021). The procedure follows four potential pathways of moisture feedback based on sectoral land use in the SSPs (Riahi et al., 2017).
The four input data pathways were SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 (Seland et al., 2020). The NorESM2 model outputs were simulated with the land and vegetation components from the Community Land Model version 5 (CLM5) (Lawrence et al., 2019).

**Paper III:** I investigated the magnitude of the climate change effect on soil-moisture dry risks amidst changes in the PBs. I modelled interactions of climate and water flows, by forcing LPJmL with climate and sectoral data from four GCMs (five coupled frameworks) in the ISIMIP3b protocol, namely CanESM5, CNRM-CM6-1, CNRM-ESM2-1, EC-Earth3, MIROC6 (Lange and Büchner, 2022). I used the high (no mitigation policy) climate scenario RCP 7.0 to simulate climate change-induced shifts in green water for the end of the 21st century. These high climate change transgressive simulation set-up followed the approach in (Porkka et al., 2024b; Richardson et al., 2023), which accounts for grid cells to experience drying risks, or here referred to as, dry departures in comparison to a Holocene-like state. Further, the paper introduced a crop-specific green water scarcity assessment by comparing the crop water demand against available water, to see if dry departure regions correspond to green water scarcity regions.

**Paper IV:** I developed management scenarios with LPJmL with a focus on green water management. I forced the LPJmL with the ISIMIP2b protocol that comprises of daily climate data from HadGEM2-ES (Frieler et al., 2017; Jones et al., 2011). I analyse based on RCPs 2.6 and 6.0 to represent CO₂ emission levels in the 21st century. The analysis involves mapping current and future trends in green water flows and stocks, an analysis of water efficiency per harvest and a comparison of conventional farming against rainwater management across time and scale.

5.3 Limitations

Despite its valuable insights into the water cycle, plant growth, and crop production, the LPJmL model has inherent limitations. These include the need for model calibration, which can introduce uncertainties in regions of the world where observational and process data are lacking. The simplification of complex real-world processes in the model may lead to inaccuracies in representing the water cycle and plant growth, and the model’s global scale may not accurately capture local hydroecological dynamics, which could affect the precision of crop production predictions. Furthermore, the quality and availability of input data can significantly impact the model’s performance in simulating these processes. For instance, the SSPs have been criticised for not capturing diverse enough perspectives (Palazzo et al., 2017; Pedersen et al., 2022).

The computational intensity of the combined modelling approach I have developed here may limit its practicality for certain applied studies. It is crucial to note that the results from the linked model frameworks I have used should be interpreted with caution in sustainability application contexts. They provide insights under specific conditions and assumptions but should not be viewed as absolute predictions of the water cycle, plant growth, or crop production. Instead, they should be used as a guide to understand potential trends and patterns, contributing to the broader understanding of these complex systems.
Summaries of the thesis papers

Papers I to IV have chronologically been instrumental to answering my research questions. In Paper I, I aimed to understand the current interactions between water, agriculture, and rainforest ecosystems in Africa. I extensively mapped the current sources of African agricultural rainfall, emphasizing the crucial role that ecosystems like rainforests play in supplying water for agricultural production. Paper II provides a global perspective, mapping both current and future atmospheric moisture feedback trends and tracking the dynamic interplay of moisture feedback influenced by land use change and climate change. This helps to better understand of whether water is affected by, and thus, a ‘victim’, of change from climate and land use changes. Paper III extends the exploration of the significance of green water to terrestrial water resilience. The PB framework is used to analyse how the global-scale dynamics of human-driven climate change and land use change (historical) lead to loss of green water resilience and affect water for food production. In Papers II and III, I seek a better understanding of temporal and spatial global changes and their implications on African water-agriculture interactions. I have made assessments of interactions at a global level due to the complex nature of water in the biosphere. Finally, Paper IV investigates how sustainable rainwater management practices could improve the green water potential to meet food production demands. This paper is an African assessment that highlights the existing potential of green water to meet the SDGs in Africa. Fig. 5 provides an overview of the scope of research papers discussed in my thesis.

Figure 5. Schematic illustration of manuscript arrangement and their relationship. Paper I, covers Africa and investigates moisture recycling and agriculture. Paper II is a global investigation of atmospheric moisture recycling and how it is influenced by climate change and land use. Paper III is a global assessment on the linkages between climate change, green water PBs, and sustainability. Paper IV take an African regional perspective to assess the green water potential for achieving the SDGs.
6.1 Paper I - Rainforests feed Sub-Saharan Africa

In Paper I, I asked where is water an 'agent' of change on which people depend? While analysing the precipitation-shed for African agricultural land, I found a strong locally derived moisture feedback (>40% for the Congo rainforests and >60% for the Indian ocean coast off Mozambique). This means water plays a key role as an 'agent' in ensuring a strong local moisture recycling and distribution to remote downwind agricultural land. Further I ask what types of water ('blue and green') is important for African agricultural production, I found 90% of agriculture production is green water dependent. I inquire where are the sources, and to what extent does each supply water for agriculture? I found oceanic sources having higher moisture source of >60% with hotspots of Mozambique and the Red Sea (Fig. 6.a). At terrestrial sources the Congo Rainforest not only provides more than 20% of moisture required in agriculture, but it also buffers agricultural land within the evaporation-shed, against dry spells (preventing water from becoming a victim of change to agricultural dry spells (Paper I)).

In this thesis, I develop and apply the combined LPJmL/UTRACK methodology for connecting source and sink regions and hydroclimatic regimes, tracking moisture from rainforest-covered areas to agricultural land and natural vegetation. I used MODIS land cover data (MCD12Q1), resampling it from its original 500 m resolution to 0.5° resolution (50 x 50 km grid) for use as input to the dynamic global vegetation and moisture tracking models. I calculated the ratio of rainforest precipitation contribution to different crop functional types on agricultural land and examined seasonal and monthly patterns in the forest moisture contribution.

![Figure 6. The African precipitation-shed and evaporation-shed during the period 2008–2017 – (a) the annual agricultural precipitation-shed expressed as percentage of moisture that precipitates over agricultural areas; (b) the annual tropical rainforest evaporation-shed in mm/year. The figure is adopted from Nyasulu et al., (2024) and is reproduced under a CC BY 4.0 licence.](image)

In the discussion, I develop the argument that maintaining the African rainforest is critical for Sub-Saharan African agriculture, both directly as an essential moisture source supporting food production and also indirectly by helping to stabilize the region's social and political conditions. I suggest that the combined analysis of precipitation-sheds and evaporation-sheds provides valuable information for the transboundary regional management and governance of land and water resources.
6.2 Paper II - Climate and land use change decrease future moisture feedback

In Paper II, I asked to what extent water is a 'victim' of global changes arising from climate change and land use change? I found that the global terrestrial moisture recycling ratio decreases with the severity of the SSPs, with an estimated decrease of 2.1% for every degree of global warming (Paper II). The Congo basin presents an intriguing case. Climate change under SSP 3 (with over 50% forest cover change) and SSP 5 (with over 20% forest cover change) will result in a 3% decrease in precipitation in the Congo basin compared to its current state. Additionally, I posed the question, what is the future pattern of atmospheric moisture provision and feedback? While it is diverse across the continent, for the Congo basin, future patterns of atmospheric moisture provision will be compensated by an increased influx of moisture from the Atlantic Ocean. However, if large-scale deforestation occurs, it will require little additional CO₂ emissions, to impact precipitation (decrease levels), despite an overall projection of a 7% reduction in terrestrial precipitation recycling ratio.

The Congo land cover change scenario could shift the dominance (Fig. 7.e) back to the land, as the decrease in evapotranspiration would result in land dominance of drying. In the context of the Congo basin, 'land dominance' refers to the situation where changes in the land, such as deforestation, have a significant impact on the climate, specifically on drying or wetting patterns. If large-scale deforestation occurs with little additional CO₂ emissions, the amount of water (evapotranspiration) could decrease significantly. This decrease in evapotranspiration would reduce the amount of moisture recycled back into the atmosphere, leading to less precipitation, or drying. This drying effect would be dominated by the changes on the land (i.e., deforestation), hence the term 'land dominance of drying.' In other words, the drying pattern is primarily driven by changes on the land rather than changes in the ocean or atmosphere. Contextually, climate change and land use disturb water cycle (i.e., water becomes a victim of change), in return these water flow changes might disrupt water flows and distributions to agricultural land (i.e., water becomes agent of change, as in paper I), that might fail to deliver water ‘provisioning’ services to agriculture (water provision services or source of resilience).

On one hand, climate change (SSP3-7.0 and 5-8.5) and land use affect ('victimised') the water cycle by decreasing the precipitation recycling ratio by 7%. On the other hand, the spatial and temporal distribution of water flow and stock, that are driven by water itself (water as ‘agent’) are compromised, resulting in shift toward land dominated drying, affecting resilience by changes in of water flows and stocks.

Historical assessment has shown that atmospheric moisture transport is highly influenced by land use and climate change (Findell et al., 2017). Paper II, therefore, explored future developments of water availability under four future climate scenarios, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, to gauge the response of moisture feedback to varying climate change and socio-economic conditions. Using multiple scenarios offered a range of possible futures that can inform policy planning. Here I compared the first ten years (2015–2024) from the SSP2-4.5 scenario (the 'middle of the road' scenario that corresponds closely to what is expected under current policies; Riahi et al., 2017) to mid-century and end of century for all four scenario pathways.
6.3 Paper III – Rainfed agriculture is at risk of green water boundary transgression.

This paper is a collaborative manuscript co-led with my PhD colleague Arne Tobian, who has a background in Physical Geography. We investigate the impact of climate change on green water resilience loss. We question whether the transgressions of the green water PB under extreme climate change affect green water ‘provisioning services’ for food production. Our model results indicate a significant ($p <= 0.05$) increase in dry deviations from the preindustrial baseline, under increasing climate change (RCP7.0) by the end of the century, compared to the transgressed areas at the end of the historical period. We also explore the synergies and trade-offs in strategies to secure green water for food while building water resilience within PBs.
We demonstrate that the world is experiencing a high dry deviation from Earth’s long-term baseline with increasing climate change, which has direct societal impacts on food production. Approximately 30% of all global land areas, currently inhabited by ~24% of the global population and producing ~28% of global harvest, are projected to face dry deviations by the end of the century under the RCP7.0 climate change scenario (Fig.8). Likewise, over 90% of water use in the affected area is green water. The risks of landscapes drying due to climate change and green water boundary interactions pose a threat to the predominantly green water agricultural system of the SSA region. We argue that PB interactions impact water provision services to achieve SDG 2, but we notice gaps within the SDGs in representing green water in its strategy.

In Paper III we further interrogate the current notion of operating ‘within’ the safe space demarcated by in line with the notion of a ‘dynamic maneuvering risk space’. A prognosis, where shifts in the already-breached climate change boundary led to more transgression of the green water boundary.

We carried out a three-step analysis, first investigating the climate change-induced interactions between the green water PB and climate change PB from a global perspective. LPJmL is used to map the regions of the globe susceptible to dry deviations of green water under climate change (RCP 7.0) by 2100. A local dry deviation in green water is registered when a month has less plant- available soil moisture than the lowest 5% percentile of the preindustrial baseline, following Wang-Erlandsson et al., (2022). Our analysis testifies that 31% of the terrestrial land surface is subject to a significant increase in dry deviations by the end of the 21st century, when compared to the recent past. We then assess green water scarcity by comparing CFT water demand and supply. Finally, we analyze socioeconomic implications with a hotspots approach. Our interpretations focus on the regional scale, and the African context. Our analysis shows the potential of interactions to amplify human impacts on PBs, and thereby, pushing the Earth system further away from safe Holocene-like conditions. This gives insights into major trade-offs for securing green water for food production, amidst climate change and green water resilience loss.

This emerging spatially resolved understanding of PBs interactions encourages discussions as to what trade-offs to accept and what synergies to pursue. For example, dedicating actions, such as massive soil moisture conservation globally, that may push the green water PB back into a safe operating space could take resources away from actions needed to resolve transgressing the PB for climate change. Actions may also affect water for ecological resilience at the expense of food production, whereas the SDGs are a call for action on integrated and indivisible social, environmental and economic goals. Possibilities for synergies lie within a combination of climate mitigation efforts supported by science-informed transformative actions in green water use for agriculture.
Figure 8. Changes under projected climate change (RCP 7.0) (a) global percentage of terrestrial surface affected by an increase in dry deviations of green water (mean 1985-2014 compared to 2071-2100), (b) percentage of the global green water of total CFT-based water consumption at grid cell level in %. global population living in affected areas (2015) and (c) percentage of global yields, expressed as harvested carbon in affected areas (mean 2000-2015). (d) Statistically significant increases in terrestrial dry deviations for green water. Changes were determined by comparing the ensemble median frequency of local deviations for rootzone soil moisture between the periods of 1985-2014 and 2071-2100. While orange colors indicate a significance of p<=0.05, red colors mark areas with a very high level of significance p <0.01 and land surface in white are not found to be subject to dry deviations. (e) percentage of green water of total CFT-based water consumption at grid cell level.

6.4 Paper IV – Green water potential to support achievement of SDGs

In paper IV, I asked to what extent does green water have the potential to attain the SDG on food (SDG2) and improve livelihood? My model analysis reveals that currently the green water potential is low across the continent with a ratio of yield per harvest of below a fraction of 1. I argue that regions close to zero (in this ratio of yield per harvest) are in critical low water efficiency and these regions reside in semi-arid and semi-dry humid. I call regions with low green water efficiency as areas with water potential, because there is room for increasing the potential (Fig. 9 a-d). To investigate the extent of this potential, I asked what are plausible green water management strategies? My analysis with rainwater management following the triply green revolution approach, showed an increase of up to >50% in harvest, in previously low water efficient regions (Fig. 9 e-g).

I used LPJmL to model green water management under different water-agriculture management scenarios, keeping land use constant at 2015 levels. Green water management is comprised of rainwater harvesting, mulching, limited tillage and run-off control management. To simulate future scenarios, I forced the model with climate data from RCP 2.6 (strong mitigation) and RCP 6.0 (a baseline no-climate policy scenario). Green water potential is spatially explicitly analysed as land areas that provide potential to increase yield per green water evaporation while increasing yield per harvested area. A key concept of triply green revolution is then exemplified by applying rainwater management and assessing the subsequent yield change.
My analysis depicts regions with low water efficiency (shown in purple / blue) could improve their production if the right mechanism is used. Fig.9. d-f shows the changes that result from applying rainwater management. The maps reveal hotspots of potential, namely, in parts of Sahel, semi-arid and semi-dry/wet humid regions (in Fig.9. d-f).

Across timescales, the comparison of yield change between the scenarios with and without rainwater management shows progressive changes, with low yield changes at the time of implementation and greater changes as time goes on. However, humid regions demonstrate better green water potential, as indicated by no change in yield. Rainwater management scenarios lead to a doubling in agricultural production (a significant indicator for SDG 2) in areas that previously showed low green water potential (Fig.a–c), but in other areas production declines. Further analysis into regions of decreasing yield showed that excessive water application encourages nitrogen leaching and decreases nitrogen uptake by plants. Therefore, to increase water productivity, caution should be taken not to exceed levels that can have negative impacts on both moisture and nutrients uptake (Molden, 2013).

Figure 9 (a – d) Green water efficiency assessed as sum of yield from 12 crop functional types (CFTs) per unit green water use, for periods (a) 1990–2005, (b) 2015–2029, (c) 2050s, and (d) 2090s. Each pixel or grid cell is analyzed at individual cropping seasonal level for each CFT for the year. (e - g) shows yield change comparison between conventional farming under RCP2.6 against rainwater management yield for periods (e) 2015 – 2029, (f) 2050s, and (g) 2090s.
7 Insights and Contributions

“Anyone can be a millionaire; it just depends which currency you are using”
—Michael Nahashon

This section highlights key insights and contributions from the thesis.

7.1 Improved methods and approaches for assessing green water status

My thesis advances water assessment for agriculture research by linking moisture recycling (atmospheric) and hydroclimatic regimes (landscape) assessments in agriculture. So far, water assessments in agriculture have mainly been dominated by assessments of visible blue water (De Fraiture et al., 2010; Hanasaki et al., 2013; Pereira, 2017; Wada et al., 2016). In the past decade, green water has become more recognized (Falkenmark and Rockström, 2006; Molden, 2013; Rost et al., 2008). Nevertheless, most of the existing literature on green water assessments has been dedicated to moisture feedback (transpiration) processes and root-zone soil water availability to vegetation (Gerten et al., 2020, 2011; Haddeland et al., 2014; Pfister et al., 2011; Rost et al., 2008; Singh et al., 2020). My work extends from previous efforts that link land-atmosphere assessment of water in agriculture (Bagley et al., 2012; Keys et al., 2012; Oliveira et al., 2013). I have connected the atmospheric and land assessments. In particular, I have shown in a spatially explicit manner that rainforests offer multiple hydro-ecological functions, providing moisture that sustains both local and distant agriculture and supplies ecosystems’ water consumption demand. This multifunctional ability of rainforests complements their climate benefits through carbon sequestration and biodiversity benefits by harbouring species. I have traced the journey of moisture from rainforests to the respective downwind agricultural lands and the crop consumption demands in those landscapes (Paper I).

Further, together with the team of researchers who developed the initial UTRACK model, I have developed a new version of UTRACK for analysis of future terrestrial moisture recycling, advancing understanding of precipitation recycling and moisture availability under different future climate scenarios (Paper II).
Furthermore, my thesis contributes to green water scarcity assessment by targeting crops specifically. Previous studies in green water scarcity applied a post-analysis using LPJmL evapotranspiration and crop water demands from a separate green and blue water model, WATNEEDS (Chiarelli et al., 2020). This approach can be prone to shortcomings due to different model assumptions in the models being used. The advancement in my work is that I and my co-authors have analysed crop-specific water demand against water supply using a dynamically coupled approach. This approach ensures that analysis uses consistent input data, and the model assumptions allow for more realistic representation of feedback. The research has also contributed to the improvement of LPJmL by incorporating a coupled analysis of plant water demand and supply, key metrics for assessing green water scarcity.

The application of biogeophysical Earth system analysis tools, LPJmL and UTRACK, to global sustainability via the RCP-SSP scenarios offers policy-relevant insights about green water status now and in future. In addition to promoting further model development to incorporate atmospheric dynamics (UTRACK) in DGVMs, my research therefore also points to the need to combine moisture recycling and land cover modeling with analysis of social consequences in the context of sustainability goals.

7.2 Analytic insights about changing drivers of water change: Land-Atmosphere interactions for water and agriculture assessments

The combination of dynamic global vegetation models and moisture tracking models offers valuable insights on green water resilience. Using a combination of moisture recycling methods with landscape assessments of dominant water flows (hydroclimatic regimes) offers new avenues of looking at water management agriculture. Moisture recycling analysis provides a better understanding of factors (like deforestation) that adversely affect water availability, which I have termed the ‘victim’ role of water. My analysis also gives insight into how blue and green water drive moisture feedback, a key element for hydroclimatic regimes. At landscape level, understanding the dominant water regime can equip downstream actors to utilize the currently available dominant flow (green or blue water) while planning for potential future flows in changing hydroclimatic regime.

Current transboundary water governance is dominated by blue water, with the Nile and Zambezi river basins as notable examples (Saruchera and Lautze, 2016). The concept of transboundary atmospheric moisture transport, also known as ‘atmospheric rivers’, often lacks representation in most policy and governance management plans (Keys et al., 2017). **Paper I** contribute to this field by illustrating the teleconnection of moisture feedback between nations, as discussed by (Dirmeyer et al., 2009; Keys et al., 2012; te Wierik et al., 2021). It does so by explicitly mapping the linkages of cross-boundary moisture sources from the Congo rainforest (and patches of rainforest in Ethiopia and Liberia) to remote agricultural landscapes across national boundaries.
7.3 Conceptual advances on water resilience and changing sustainability risks

Water is a victim of global changes. Global changes are projected to decrease terrestrial moisture recycling, intensifying risks for water-related crises in agriculture and natural ecosystems, particularly in moisture-dependent regions. These changes not only threaten water’s existence but also amplify the severity of the global changes themselves, making water both a victim and a catalyst of global changes.

Despite the PB framework’s ability in analyzing these interactions and risks, the framework has been criticized for its limited scalability and regional applicability. However, my research has utilized models to enhance the PB framework’s application at the regional level (Paper II). Furthermore, I have bridged the research gap by conducting a feedback analysis of the consequences of PB interactions. I have linked PB interactions to sustainability.

My research findings can be applied to the growing body of research of regime shifts. I have shown that at a global scale, changes of terrestrial ecosystems, especially rainforests, could lead to significant shifts in water availability for agricultural moisture provision services (Paper I and II). Reduced local rainforest moisture recycling can switch tropical rainforests from a carbon sink to a source due to drought-induced forest loss. Similarly, local droughts due to collapse of moisture sources can propagate crop-failure and food insecurity. These insights into human impact on tipping elements, key Earth subsystems, may destabilize the planet's current state (Paper III).

Insights on green water resilience for social-ecological systems offer prospects to facilitate the achievement of SDGs and water governance reforms. My thesis explores the intersection of knowledge and practice, using dynamic global vegetation and moisture tracking models to understand green water resilience in social-ecological systems. These insights are crucial for achieving SDGs and implementing water governance reforms. The research advances the interface between the biogeophysical understanding of the Earth’s system and its interaction with policies represented in SDGs. This ‘systems thinking’ approach is central to SDG advocacy, with the ultimate goal of achieving them (Cornell et al., 2013; Lim et al., 2018; Sanneh, 2018). A better understanding of green water is needed to inform humanity’s future safe maneuvering space in relation to the PBs that have already been transgressed.

Three key main points related to achieving SDGs in SSA are poverty alleviation, zero hunger, and building water resilience for food and ecosystem sustenance. My research provides a system understanding of the interplay between water, food, poverty, and the environment, demonstrating that green water is responsible for over 90% of agricultural production in SSA and is the sole supplier of water demands across natural vegetation growth (Paper I and IV). Papers I, III and IV contribute to the research on achieving SDGs in Africa by analyzing water distribution for food production. This is done by providing spatially explicit assessment of how green water availability, use, future trends, and management options can advance SDG 2 through doubling food production.
7.4 Science-informed advocacy for a triply green revolution for sustainable food

There is a need to transition from the conventional water paradigm, which solely focuses on blue water, to recognizing the significant potential of green water (Paper IV) as an equally vital water regime. Despite its invisibility, understanding and incorporating green water activities and processes are crucial for pinpointing its impact. Shifting the focus to green water, by e.g. implementing rainwater harvesting and other options to increase the potential of green water for food production, will facilitate policy reforms that are advocated specifically for its management. Proper representation of green water in SDGs can strengthen member states' targets and investments towards this resource. A growing emphasis on sustainable finance and nature recovery poses an opportunity to integrate green water as a pivotal element in defining water responsibility for socio-economic progress and environmental sustainability.

The gains in water productivity for SSA can contribute to climate-driven water scarcity and ecosystem sustainability. Given that a majority of SSA's population is employed in the informal agricultural sector, improving water productivity not only provides higher yields but can also serves as a source of household nutrition and income under favourable markets access. This underscores the importance of investing in green water as a viable strategy to complement to poverty reduction strategies through agricultural development.

Current rainfed agriculture suffers from low productivity and unsustainable water use practices, leading to significant soil moisture loss and nutrient depletion. However, upgrading rainfed agriculture through effective rainwater management techniques can address these challenges. Implementing sustainable management practices such as soil moisture conservation and water use efficiency enhancements, as outlined in Paper IV, can increase yields per unit of transpiration and mitigate soil nutrient loss. Such rainwater management can shift water productivity and translate to yields of more than 50% in some regions.

Despite a volume of information and multiple initiatives targeting rainfed agriculture management, there remains gaps in the current African agriculture policy landscape. Even with all the background knowledge, the challenge resides in dealing with difficult decisions. For instance, should the emphasis be put on water for food over ecosystems? Or, how about vesting more on blue water over green water? We do not know fully what the future holds, as we do not know national level decisions of the future. To account for this, throughout my thesis papers (paper II, III, and IV), I used scenario pathways to provide multiple future landscape on which policy actions can be based.
Conclusions and Outlook

“I have so rarely been afforded the right of farewell,”
—Ta-Nehisi Coates, The Water Dancer

In my thesis, I have looked at water resilience for social-ecological system with focus on green water’s potential on food production. Together, the analyses that I have presented show that it is possible to meet the food demand, but it will require a hefty transformation of today’s agricultural systems. The message that comes out clearly from my thesis is the need to shift perceptions about water for agriculture and look beyond blue water, which is highly advocated for in irrigation systems and similar development policies and investments. Such a change in perception will require readjusting strategic planning and investment in green water.

The selection of type of water use in specific landscapes should be both pragmatic and science-based, following evidence on trends and projections of water use and resource availability from a combination of meteorological and hydroecological science. Likewise, soil health management will become more critical when adopting rainwater management systems that are locally driven. The combination of the two water and soil management will be key to avoid the economic barrier that exists in SSA. If humanity foregoes taking relevant actions, placing water as a main ingredient to global resilience loss, it could lead us into unimaginable territories characterized by crises for humankind and the PBs.

I have looked at SDG 2 from the perspective of doubling food production (SDG Target 2.3). Another related issue is that of food waste management, that impacts attainment of SDG2. But that lies outside the remit of my thesis study. Furthermore, to take a holistic perspective, it is important to note that food security does not entail nutritional balance, which would be required to alleviate malnourishment challenges that continue to perpetuate in Africa. Lastly, I acknowledge the complexity of poverty alleviation in SDG 1, my findings on yield increase for farmers can therefore work under conducive economic and policy conditions.

The future of sustainability governance relies on uncompromised rigorous and transformative steps to navigate back into the safe operating space sustainably while justly providing all humanity with a healthy well-being. Water is pivoted to supporting these goals, due to the innate and extrinsic roles it plays in building the resilience of social-ecological systems. Building water resilience therefore calls for actions at every scale, from local to policy level, from civil society to non-profit and business sectors. However, recognising that water services (provision, victim, and agent services) are intricately connected, provides a foundation for looking at water not in isolation, but as part of the social-ecological system.
Beyond the scope of my thesis on mapping the biogeophysical state of water and its roles in building social-ecological resilience, I have identified **three next steps** of my research clustered around advancing research methods, transdisciplinary nature recovery, and practices:

**i. Advancing research methods**

There are prevailing research gaps in the body of sustainability on how the PBs interactions are studied (e.g. the need for localized assessments, feedback analyses of the PB interactions, uncertainty analyses, novel entities assessments) (Lade et al., 2020). I have shown that climate and green water boundary interactions impact agriculture food production. Future research should therefore refine and increase accuracy of the models. As the models become more robust, further advancements in the feedback analysis methods should look at the impact of other boundaries interactions on food production and human welfare in general.

Enhanced observation in plant water consumption: There is need for further exploration and advancements for both on-field and satellite techniques for observing and quantifying plant water consumption. Despite advancements in remote sensing (Cheng et al., 2023; Roerink et al., 1997; Virnodkar et al., 2020), field experiments need to be performed to improve accuracy and understanding of eco-hydrological processes alongside satellite imagery because they are specific to plant type and hydroclimate regime they grow.

Further DGVM developments are required in representing a coupled simulation of the moisture recycling, hydroclimatic landscape regime, and incorporation of agents’ behaviors. While there are some advances within the LPJml community at Potsdam Institute of Climate Impact Research (Donges et al., 2020), I believe extending these developments to other DGVM will provide robust scientific grounding (e.g. replication with other modeling approaches).

**ii. Transdisciplinary research with focus on green water investment and ecosystem recovery**

My thesis has advanced the existing knowledge on the links between ecosystems and green water along with the climate and human threat to ecosystem loss. Future research therefore has potential, in SSA, to ensure ecosystem recovery and resilience in favor of building climate and green water co-benefits. Therefore, a focus on developing cases that combine ecosystems and green water sustenance will be beneficial. However, this will involve transdisciplinary links between fields such as economics, biodiversity, finance, Earth system sciences, and stakeholders. The focus should be on vulnerable and crucial ecosystems for agricultural water supply. The research will also have to explore the benefits of green water activities beyond agricultural production, including ecosystem and climate (above and below ground carbon storage) advantages.
Research in innovative financing mechanisms and investment strategies for green water initiatives can ensure sustainable practices and socio-economic development. The integration of these areas could provide a comprehensive understanding of the interplay between economic viability, climate change impacts, and nature recovery strategies, thereby informing sustainable business practices, policymaking, and the growing field of sustainable finance.

iii. From knowledge to policy and practice

My thesis (papers I, III, IV) highlights the overlooked role of green water in achieving global (SDGs) and SSA policy strategies. Future priorities should focus on providing robust evidence of green water’s importance to social-ecological systems and integrating green water into policy strategies, which could also facilitate financing for green water and ecosystems. Furthermore, these priorities should engage local actors, like smallholder farmers, in strategy development and implementation.

Communicating science through speculative, resilience-focused literature, such as the anthology ‘Mombera Rising Anthology (Mhlema et al., 2024)’ to which I contributed during my PhD, holds significant power. As I look ahead, my research interests are increasingly leaning towards the production of robust scientific evidence that can be seamlessly translated into impactful applications within policy, speculative writing, and gamification.
Epilogue

"You can't write a script in your mind and then force yourself to follow it. You have to let yourself be."
— Chimamanda Ngozi Adichie, Half of a Yellow Sun

I was drawn to multidisciplinary research by the allure of exploring different domains of knowledge, from Finance, Economics, Public Health, Agriculture to Environmental governance. I never felt comfortable in the narrow confines of a single discipline, and I always sought to expand my horizons. My background in Economics and statistics gave me the tools to apply social science concepts in various fields. The challenge of working with multiple disciplines was a source of inspiration for me, as I found my niche in the complexity of the world. What began as a simple curiosity to understand how the Earth operates, led me to pursue a PhD. Throughout my PhD journey, I was haunted by my development project practice mindset, and I often felt torn between doing science and making a difference. This is reflected in my research work and writing style, which always aim to show the impact of my research on the real world. I guess that is the essence of sustainability science scholarship.

Malin Falkenmark
I owe my achievements and vision to a giant, Malin Falkenmark, who unfortunately passed on during my PhD, who guided me and supported me. I am grateful for her kind heart, her wisdom and generosity. Whether you call me Mr Blue-Green, as some of my siblings do, a name I have come to embrace. It feels surreal to remember the hours I spent in her old Office (at Stockholm Resilience Centre’s [SRC] old housing at Kräftriket), as she explained just about everything I could not possibly imagine about water. She understood my interest in practice beyond science, and she was instrumental in connecting my research with Stockholm International Water Institute and Stockholm Environmental Institute, where I learned a lot from other perspectives. She always made me feel confident and valued, even when I doubted myself or my knowledge. She encouraged me to share and improve my ideas, no matter how simple or naive they might seem. She helped me recognise that in every room, there is someone who can enrich me with knowledge beyond my expertise. I have experienced a similar atmosphere with my supervisors, including Ingo Fetzer, Johan Rockström, and Deiter Gerten, as well as the mentors who have supported me along the way, such as Sarah Cornell, Lan Wang-Erlandsson, and Henrik Brundin.

Malin will always have a special place in my heart.

Reflecting on my sustainability research journey, I see beauty in the chaos of dealing with dynamic societal and natural systems. While my background is quantitative, I have learned to think beyond numbers. We cannot measure everything, and my research aims to capture and interpret global changes from a value-neutral perspective, examining how they impact our livelihoods. This also means that my research is not without controversy, and I have faced many challenges and criticisms throughout my PhD journey. Sustainability science is a contested field of scholarship, with many debates and disagreements within and outside its boundaries, which go beyond this epilogue.

During my time as a program officer at SwedBio, a program at SRC, I had the privilege of working at the policy-research interface. This position not only excited me, but also challenged
me due to the complex and impactful work that SwedBio does in advocating for biodiversity, fisheries, agroforestry, and indigenous communities at both policy and practice levels. This demonstrates the diverse applications of sustainability scholarships.

Pivoting on Science, I have had the privilege of participating in research study visits, academic conferences, courses, and summer schools. Furthermore, I have attended yearly PhD cohort annual meetings, which were briefly suspended during the COVID-19 outbreak, as were many other aspects of life. COVID 19 came at a cost to my research methodology, as it was difficult to carry out the project’s planned study visit to the United States Geological Survey to learn the methodologies intended for the PhD project. To address the issue, I initially implemented LPJmL from the Potsdam Institute of Climate Impact Research in Germany, along with the WAM-2Layer moisture tracking model. However, during the WAM-2Layer application, I noticed inconsistencies that could affect my research results. As a result, I switched to the UTRACK model after spending a long time rectifying WAM-2Layers issues. It is noteworthy that migration issues remain an Achilles’ heel to this day. Like other researchers facing similar challenges, I have encountered difficulties related to migration when attempting to extend work permits, conduct research visits, or attend conferences. However, these obstacles can be overcome, as I have done with COVID-related delays and changes to my research methodology.

In positioning myself in sustainability research, I aim to contribute towards the advancement of this field and the solution of pressing sustainability challenges faced by the global community. The focus of my research will be to engage researchers in the Global South and to invite others to collaborate across disciplines and across borders. I hope that my research can positively impact the lives of those who depend on the water resources I have studied, as well as the health of the ecosystems that sustain them. Sustainability science is not only a scientific endeavor, but also holds moral and ethical value, and we have a responsibility to act on our knowledge and values.
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