

### The Author



Rooted in a fascination with living systems, Simran Sekhri studied Botany at the University of Delhi, before pursuing two master's degrees in environmental and resource management in India and Germany. She then joined the University of Hamburg for her doctoral research, where she investigated soil water dynamics in the sandy drylands of northern Namibia. Her dissertation examined how land use and management practices shape water availability under drought, across scales ranging from field experiments to soil-plant-vapor interactions. Alongside her research, she has developed an active interest in science communication.

S. Sekhri

## Simran Sekhri

# Land-Use and Land Management Effects on the Soil Water Dynamics of Northern Namibia



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# **Land-Use and Land Management Effects on the Soil Water Dynamics of Northern Namibia**

**DISSERTATION**

with the aim of achieving a doctoral degree  
at the Faculty of Mathematics, Informatics and Natural Sciences  
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at University of Hamburg

submitted by

**Simran Sekhri**

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## Abstract

Sandy soils that dominate the semi-arid regions of northern Namibia, are characterized by low water holding capacity and rapid infiltration, which inherently limit plant available water. These limitations are intensified by high temperatures and strong atmospheric evaporative demand, together with rainfall variability and recurrent droughts, placing substantial pressure on smallholder farming systems. Conservation agriculture has therefore been promoted as a water conserving approach to improve soil water dynamics, enhance soil fertility and sustain crop production. However, its hydrological functioning in sandy drylands remains insufficiently understood and significant knowledge gaps persist on how long-term land-use and management practices influence soil water dynamics and plant water availability under water limited conditions.

This dissertation investigated soil water dynamics across complementary spatial and experimental scales. Field studies compared traditional agriculture, conservation agriculture and near-natural woodland systems to quantify land-use effects on infiltration, soil water content and evapotranspiration. In parallel a dune transect study examined how soil water dynamics differ across dune topographic positions, dune crest, slope and interdune, with interdunes emerging as key zones of hydrological accumulation. At the management scale, trials at Mashare evaluated the effects of mulching, minimum soil disturbance and rhizobial inoculation on soil water dynamics and crop yield. Greenhouse experiments explored how organic mulches and rhizobial inoculation modulate soil water dynamics and plant water use under drought, while, soil column experiments tested whether plants can utilize water vapor under extreme drought, extending survival beyond the depletion of liquid water under severe drought.

The findings showed that conservation agriculture primarily increased the temporal persistence of near surface soil moisture rather than altering total evaporative fluxes, thereby improving soil water retention and plant available water under drought conditions. Within conservation agriculture, mulching emerged as the most effective intervention: a combined wood chip and wheat straw mulch increased water use efficiency and vegetative development, although these gains did not translate into reproductive success under greenhouse conditions. Rhizobial inoculation enhanced plant vigor and increased grain yield at Mashare, complementing the hydrological benefits of reduced disturbance and mulch. At soil-plant-vapor interface, plants accessed water vapor from a hydraulically isolated water reservoir under extreme drought, and

mulching strengthened this effect with the utilization of vapor translating directly into extended survival beyond the point of liquid water depletion, revealing a rarely quantified mechanism of water acquisition by young saplings in sandy soils. Beyond management interventions, the dune transect study showed a tendency for interdunes to hold slightly higher soil moisture than dune crest and slope positions, reflecting a potential influence of topographic variation on water accumulation.

Together, these findings provide a multiscale understanding of soil water dynamics in sandy drylands and demonstrate that conservation-oriented practices improve near surface water retention, prolong plant available water and strengthen the hydrological resilience of dryland cropping systems. The dissertation advances empirical evidence for adaptive soil water management under climate variability and highlights the value of combining reduced soil disturbance, surface protection and biological inputs to support sustainable, climate-resilient agriculture in vulnerable dryland systems.

## Zusammenfassung

Sandböden, die in den semiariden Regionen Nordnamibias dominieren, zeichnen sich durch eine geringe Wasserspeicherkapazität und eine schnelle Infiltration aus, was die pflanzenverfügbare Wassermenge begrenzt. Diese Einschränkungen werden durch hohe Temperaturen und eine starke atmosphärische Verdunstungsnachfrage sowie durch Niederschlagsvariabilität und wiederkehrende Dürren verstärkt, was kleinbäuerliche Bewirtschaftungssysteme stark unter Druck setzt. Konservierende Landwirtschaft wird als Wasser effizienter Ansatz gefördert, um die Bodenwasserdynamik zu verbessern, die Bodenfruchtbarkeit zu steigern und die landwirtschaftliche Produktion zu stabilisieren. Dennoch ist das hydrologische Funktionsverhalten von konservierender Landwirtschaft in sandigen Trockengebieten bislang unzureichend verstanden, und es besteht Forschungsbedarf hinsichtlich der Frage, wie Landnutzungsformen und Bewirtschaftungspraktiken die Bodenwasserdynamik und die Pflanzenwasserverfügbarkeit unter wasserlimitierten Bedingungen langfristig beeinflussen.

Diese Dissertation untersuchte die Bodenwasserdynamik auf verschiedenen räumlichen und experimentellen Ebenen. In Feldstudien wurden traditionelle Landwirtschaft, konservierende Landwirtschaft und naturnahe Waldflächen verglichen, um deren Einfluss auf Infiltration, Bodenwassergehalt und Evapotranspiration zu quantifizieren. Parallel dazu analysierte eine Dünen-Toposequenz, wie sich die Bodenwasserdynamik an verschiedenen topographischen Positionen, Dünenkamm, Dünenhang und Interdüne unterscheidet, wobei sich Interdünen als Zonen hydrologischer Akkumulation abzeichneten. Auf der Managementebene wurden in Feldversuchen am Standort Mashare die Wirkungen von Mulch, minimaler Bodenbearbeitung und Rhizobien-Inokulation auf die Bodenwasserdynamik und den Ertrag untersucht. In Gewächshausversuchen wurde analysiert, wie organische Mulchmaterialien und Inokulation die Bodenwasserdynamik und die Pflanzenwasseraufnahme unter Trockenstress beeinflussen, während Bodensäulenexperimente prüften, ob Pflanzen unter extremem Wassermangel Wasserdampf nutzen können und dadurch ein Überleben über den Zeitpunkt der vollständigen Erschöpfung von Flüssigwasser hinaus möglich wird.

Die Ergebnisse zeigten, dass konservierende Landwirtschaft vor allem die zeitliche Persistenz der bodennahen Bodenfeuchte erhöhte, ohne die Gesamtsumme der Verdunstungsflüsse deutlich zu verändern, wodurch die Wasser-rückhaltung und die pflanzenverfügbare Wassermenge unter Trockenheit verbessert wurden. Innerhalb der konservierenden Landwirtschaft erwies sich Mulch als die wirksamste Maßnahme: Eine Kombination aus Holzchips und

Weizenstroh erhöhte die Wassernutzungseffizienz und das vegetative Wachstum deutlich, wenngleich sich diese Effekte unter Gewächshausbedingungen nicht in einer reproduktiven Leistung resultierten. Die Rhizobien-Inokulation steigerte die Vitalität der Pflanzen und erhöhte den Kornertrag in Mashare und ergänzte damit die hydrologischen Vorteile von Mulch und reduzierter Bodenstörung. An der Boden-Pflanze-Vapor Schnittstelle konnten Pflanzen unter extremen Trockenstress Wasserdampf aus einem hydraulisch isolierten Wasservorrat aufnehmen, und Mulch verstärkte diesen Effekt; die Nutzung von Wasserdampf führte direkt zu einer verlängerten Überlebenszeit über den Punkt der Liquidwasserverfügbarkeit hinaus und offenbarte einen bislang selten quantifizierten Mechanismus der Wasserakquisition junger Pflanzen in Sandböden. Darüber hinaus zeigte die Dünen-Studie eine Tendenz, dass Interdünen etwas höhere Bodenfeuchten aufwiesen als Dünenkamm- und Hangpositionen, was auf einen möglichen Einfluss topographischer Variation auf die Wasserakkumulation hinweist.

Insgesamt liefern diese Ergebnisse ein multiskaliges Verständnis der Bodenwasserdynamik in sandigen Trockengebieten und zeigen, dass konservierungsorientierte Bewirtschaftungspraktiken die bodennahe Wasserrückhaltung verbessern, die Verfügbarkeit pflanzenverfügbaren Wassers verlängern und die hydrologische Resilienz trockener Agrarsysteme stärken. Die Dissertation bietet empirische Grundlagen für ein adaptives Bodenwassermanagement unter Klimavariabilität und unterstreicht den Nutzen der Kombination aus reduzierter Bodenstörung, Oberflächenschutz und biologischen Inputs zur Unterstützung einer nachhaltigen und klimaresilienten Bewirtschaftung in vulnerablen Trockengebieten.

## Manuscripts Related to this Dissertation

Corresponding authors are marked with \*.

### Study A:

*Accepted for publication*

**Simran Sekhri\***, Elisa Karina Albrecht, Alexander Gröngröft, Joscha N. Becker, Annette Eschenbach. Investigating soil water dynamics to improve agriculture: Namibian land-use systems under drought. CABI, Special Issue, Soil Science Cases.

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### Study B:

*In preparation (extended abstract in Manuscripts section)*

**Simran Sekhri\***, Erik Lübeck, Alexander Gröngröft, Joscha N. Becker, Annette Eschenbach. Soil water dynamics along the Kalahari dune transects in northern Namibia.

### Study C:

*Extended abstract (in Manuscripts section)*

Soil water dynamics and yield responses of cowpea under conservation and traditional agriculture in northern Namibia.

### Study D:

*Submitted*

**Simran Sekhri\***, Elisa Karina Albrecht, Jacob Kohn, Shanmugam Solaiyappan Mani, Barbara Reinhold-Hurek, Joscha N. Becker, Annette Eschenbach. Cowpea

growth response to mulching and inoculation modifying soil water balance under simulated drought.

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## Study E:

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Mulching, rhizobial inoculation and water supply shape soil enzyme activities and nutrient dynamics in Namibian sandy soil under cowpea cultivation.

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# Unifying Essay





# 1 Introduction

## 1.1 Background and Motivation

### 1.1.1 Agricultural Constraints in Semi-Arid Northern Namibia

Namibia is among the driest countries in sub-Saharan Africa (Liu & Zhou, 2021), with semi-arid conditions dominating much of its landscape (Moseki et al., 2025). Namibian climate is characterized by high interannual variability in rainfall, recurrent droughts and prolonged dry seasons (Shiimi & Uchezuba, 2025). Evaporative demand is consistently high (Wang et al., 2007), with hot summer temperatures accelerating soil water loss (von Oertzen et al., 2024). The soils are predominantly Arenosols with coarse texture, low organic matter content, loose structure and extremely low water holding capacity (Obeid & Mendelsohn, 2001; Simmonds, 2000). Together, these climatic and edaphic constraints create an environment of severe water limitations for agricultural productivity.

Moreover, water limitation in Namibia is aggravated by limited infrastructure (Shikangala, 2025) and restricted access to irrigation (Mapani et al., 2023). Only a small fraction of cultivated land is irrigated (Kaupa et al., 2022) that makes groundwater a crucial resource (Coetzee, 2023). However, aquifer distribution is uneven and many groundwater reserves lie deep below the surface, rendering extraction economically challenging (Ruppel-Schlichting, 2022). Prolonged drought spells over the past decade, including severe events in 2013, 2016 and 2019, have placed extraordinary pressure on both rural livelihoods and national water supply systems (Liu & Zhou, 2021) resulting in widespread livestock losses and severe crop failures, underscoring the fragility of northern Namibia's agricultural base under recurrent climate extremes (Shiimi et al., 2023).

Despite these limitations, agriculture remains an important source of livelihood for rural households in northern Namibia (Nair et al., 2024; Prudat et al., 2018). Agriculture is almost entirely rainfed and highly dependent on seasonal rainfalls (Mendelsohn, 2009). Subsistence farming is the dominant production system (Mendelsohn et al., 2000; Nangolo & Alweendo, 2020), with smallholder farmers cultivating staple crops such as pearl millet (*Pennisetum glaucum*) locally known as Mahangu, cowpea (*Vigna unguiculata*), sorghum and groundnut (Siyambango et al., 2022). These crops are usually grown in low-input, monocropping systems and contribute to local food security (Fortunato & Enciso, 2023). Crop productivity, however, is persistently low and highly

variable (IMF, 2025). Frequent intra-seasonal dry spells disrupt sowing, establishment and reproductive development of plants, while the weak moisture retention capacity of sandy soils exacerbates drought stress (Melo et al., 2025; Souza et al., 2024; Tankari et al., 2021). Moreover, traditional agricultural systems in northern Namibia are typically low input, relying on manual or animal drawn tillage with shallow and infrequent ploughing, limited soil cover and occasional intercropping (Paulus, 2015; Spear & Chappel, 2018; Taapopi et al., 2018). Although not highly mechanized, the combination of continuous cultivation, residue removal and exposure of bare soils in traditional agricultural practices promote rapid drying, erosion and nutrient depletion in soils (Corsi & Muminjanov, 2019). Livestock integration adds additional pressure, as crop residues are commonly grazed, preventing organic matter accumulation that could otherwise improve soil structure (Luchen et al., 2018; Riseh, 2024).

As a result, crop yields remain far below potential (Jeong et al., 2025; Rasche et al., 2023), with recurrent crop failures leading to chronic food insecurity (FAO et al., 2021). Rural households are therefore trapped in a cycle of low productivity and high vulnerability to climatic shocks (Shiimi et al., 2023). This context underscores the need for improved land-use and soil water management strategies to enhance the resilience of northern Namibia's farming systems under intensifying climate stress.

### **1.1.2 Water Dynamics of Sandy Soils**

Sandy soils present many hydrological limitations that make agricultural production in semi-arid regions particularly challenging (de Holanda et al., 2025). Their coarse texture, with large pores, results in very low water holding capacity and limited water retention in the plant rooting zone (Bockheim et al., 2020). After rainfall, water infiltrates rapidly and percolates through the soil profile, often below the depth accessible to crops (Song et al., 2018). This leads to a situation where precipitation, although often scarce and irregular, is further diminished in its effectiveness by rapid drainage losses (Deol et al., 2014). In addition, the absence of stable aggregates and low organic matter content compound these losses (Alghamdi et al., 2023; He et al., 2018).

Evaporation is another major pathway of soil water loss and its impact is especially pronounced in sandy soils (Liu & Zhou, 2021). Bare, unprotected surfaces are subject to high atmospheric evaporative demand (Sakai et al., 2009). In sandy soils, rapid drying leads to a steep decline in unsaturated hydraulic conductivity disrupting capillary continuity between surface and subsurface layers (Lehmann et al., 2008). This process leads to the formation

of a dry soil layer (Balugani et al., 2018) that restricts water stored in deeper layers from being redistributed upward to sustain plants during dry periods (Lehmann et al., 2008; Wang et al., 2020). Under extreme drought the dry soil layer progressively deepens as the evaporative front shifts downward and evaporation rates decline, while partly shielding deeper soil layers from further unproductive water loss (Or et al., 2013; Sakai et al., 2009). Under semi-arid conditions, it is not uncommon for topsoil layers to dry within a few days of rainfall (Li et al., 2010), leaving insufficient time for crops to fully utilize available water (Marcos-Garcia et al., 2024). Consequently, soil water availability is highly discontinuous, with instances of saturation followed quickly by extreme drought (Sekhri et al., 2025).

The strong coupling between infiltration, evaporation and hydraulic conductivity explains the distinctive hydrological behavior of sandy soils, where rapid water movement coexists with limited water retention (Morbidei, 2020; Wang et al., 2023). The hydraulic behavior of sandy soils is governed by their coarse pore structure and weak capillary connectivity (Or et al., 2013; Princ et al., 2024). Their saturated hydraulic conductivity is high, enabling rapid infiltration, but unsaturated conductivity declines exponentially with decreasing water content due to minimal pore continuity (Hohenbrink et al., 2023; Huang & Wang, 2024; Sakai et al., 2009). The resulting steep soil water retention curve highlights that even small reductions in matric potential causes large declines in water content (Farooq et al., 2024; Madi et al., 2018). This limits plant available water as it leads to fast transitions between wet and dry states (Fu et al., 2024; Ladányi et al., 2021; Nachum, 2025). Moreover, low specific surface area and limited adsorption capacity of sandy soils reduce water retention at field capacity, while the predominance of macropores promotes gravity-driven flow and bypass drainage (Beven & Germann, 1982; Madi et al., 2018; Pandey & Ojha, 2025). Together, these processes produce highly dynamic but transient water storage behavior, characteristic of sandy drylands.

Therefore, such soil water dynamics delineate that the effective growing season for crops on sandy soils is strongly limited, as the mismatch between rainfall events, soil water holding capacity and plant available water explain the high frequency of crop failures and the vulnerability of smallholder farming systems in northern Namibian landscape. Addressing these limitations require management strategies that conserve water in the rooting zone, reduce evaporative losses and potentially enable plants to access otherwise unavailable water reservoirs.

### 1.1.3 Current Adaptation Strategies and Limitations of Semi-Arid Farming Systems

Subsistence agricultural systems in northern Namibia, particularly in the Kavango and Omusati regions, are still dominated by traditional agricultural practices (GIZ, 2022). Farmers typically cultivate pearl millet and sorghum under low-input systems with shallow tillage and minimal residue retention (Siyambango et al., 2022). Straw crop residues are often removed for fodder, fuel or construction, leaving soils bare and prone to rapid drying (Mulumba & Lal, 2008). These practices maintain low soil fertility, exacerbate evaporative losses and reinforce the vulnerability of rainfed production to recurrent droughts (Shiimi et al., 2023).

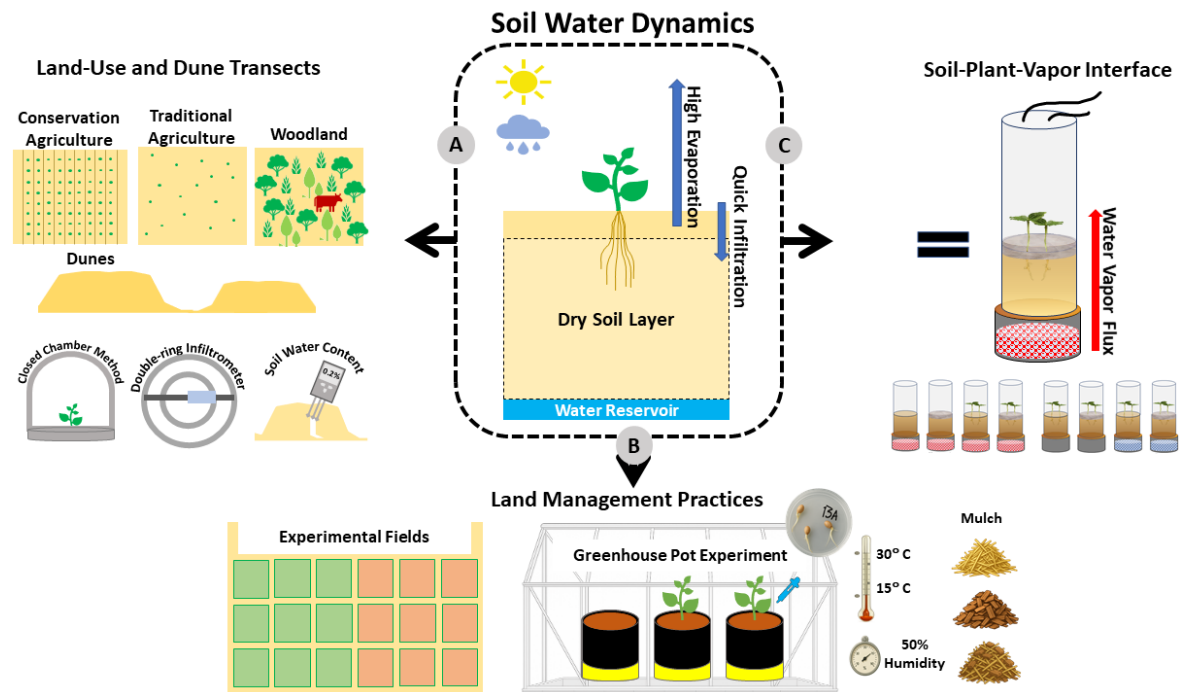
To address these constraints, conservation agriculture has been promoted as a pathway to improve drought resilience of smallholder farming systems in semi-arid northern Namibia (Taapopi et al., 2018). Conservation agriculture is based on the principles of minimum soil disturbance, permanent soil cover and crop diversification (FAO, 2025). While crop gains under conservation agriculture vary by region (Mhlanga et al., 2021; Ngoma et al., 2021), in the sandy soils of northern Namibia the potential benefits relate primarily to improved soil health, better water retention and consequent plant water use (Kudumo et al., 2023; Nonxuba et al., 2025; Teng et al., 2024; Thierfelder et al., 2013), which together can contribute to relatively higher and more stable crop yields (Demir & Işık, 2019; Kudumo et al., 2025; Shumba et al., 2024). Within conservation agriculture, mulching as a practice to cover soil plays a central role in improving soil water conservation (Prosdocimi et al., 2016; Thierfelder et al., 2013). By maintaining a continuous protective cover, mulching moderates soil temperature, reduces direct evaporation and improves topsoil water retention, allowing a greater fraction of rainfall to remain within the rooting zone (Iqbal et al., 2020; Lamont, 2005; Ramos et al., 2024; Thierfelder & Wall, 2009). Over time, the decomposition of organic mulch enhances aggregate stability and increases water holding capacity by improving pore continuity and organic matter content (Díaz et al., 2022; R. Li et al., 2020; Pavlů et al., 2021). In sandy soils, such processes effectively act as micro-scale water harvesting mechanisms, retaining rainfall in situ and extending soil moisture availability between rainfall events (El-Beltagi et al., 2022; Mhlanga et al., 2021; Rusinamhodzi et al., 2011). However, the widespread use of mulch remains constrained by limited residue availability and competition with livestock feed requirements (Luchen et al., 2018; Valbuena et al., 2012). The use of woody mulch derived from encroacher species has therefore emerged as

a promising alternative, providing both biomass for soil cover and a means of restoring rangeland productivity (Humphrey et al., 2022; Kariuki et al., 2025).

In parallel, the integration of legumes has been promoted as a key strategy to enhance soil fertility and stabilize crop production in resource limited smallholder farming systems thereby supporting more sustainable agriculture practices (Jeong et al., 2025; Rehman et al., 2019). Legumes contribute biological nitrogen fixation, enhance soil organic matter through residue inputs and diversify cropping systems, which collectively improve soil structure and moisture dynamics (Kebede, 2021; Sharma et al., 2024). Among legumes, cowpea has been promoted as a rotation crop as it is well adapted to semi-arid environments, capable of producing food and fodder under conditions of low and variable rainfall and offers short growth cycles that align with the irregularity of precipitation events (de Blécourt et al., 2019; Ritte et al., 2022). To further enhance the role of cowpea, enhancing nodulation efficiency and symbiotic nitrogen fixation capacity through rhizobial inoculation has been an effective strategy to improve plant growth and yield (Becker et al., 2024; Kyei-Boahen et al., 2017; Sarkar et al., 2023b).

Despite these potential benefits, several limitations hinder the widespread adoption of conservation agriculture in northern Namibia. The implementation of conservation agriculture is confronted by multiple constraints (Araya et al., 2024). Adoption rates remain low (Shiimi & Uchezuba, 2025), driven by limited farmer awareness of long-term benefits (Hermans et al., 2020), weak farmers extension services (Ma & Rahut, 2024) and limited technical and scientific knowledge required for minimum tillage operations and residue management (Amankwah, 2023; Baudron et al., 2015). Climate variability further complicates implementation and scaling of conservation agriculture (Araya et al., 2024; Su et al., 2021), as practices are highly localized and require adaptation to local farming systems and preferences (Brown et al., 2018). Knowledge gaps remain substantial with respect to the functioning of conservation agriculture in sandy soils, particularly regarding how management practices influence soil water dynamics, plant water availability and long-term farmland resilience under semi-arid conditions. Addressing these gaps form the core of this dissertation, which investigate the effects of different land-use systems, soil management practices and soil-plant-water interactions on soil water dynamics across the northern region of Namibia.

## 1.2 Thesis Objectives and Outline



**Figure 1:** Scheme of studied soil water dynamics across (A) land-use and dune transects, (B) land management practices and (C) soil-plant-vapor interface. Illustration by Sekhri S.

The aim of this research was to investigate soil water dynamics in the sandy soils of northern Namibia, focusing on the Kavango and Omusati regions across multiple spatial scales (Figure 1). Under field scale, soil water dynamics was examined across different land-use systems including conservation agriculture, traditional agriculture and near-natural woodlands, as well as along dune transects. Land management effects were further assessed through experimental plots built in Mashare and extended greenhouse trials, both designed to assess the influence of mulching and rhizobial inoculation under conservation and traditional agricultural practices. At a finer experimental scale, water vapor uptake and utilization were examined in controlled soil column experiments including the role of mulching in enhancing this effect. These studies aimed to advance understanding of soil water dynamics in sandy soils and to delineate the potential of conservation agriculture to strengthen drought resilience in northern Namibia.

The dissertation was organized into three main studies with distinct segments (Study A-E).

## **1. Soil water dynamics across land-use systems and dune transects**

This study was conducted in two segments.

**Study A:** Investigating soil water dynamics to improve agriculture: Namibian land-use systems under drought.

The objective of this study was to investigate two key questions:

- I. How does land-use systems influence soil water dynamics, particularly in terms of topsoil moisture retention, infiltration and surface water loss during the crop growing period?
- II. To what extent does conservation agriculture enhance water retention and regulation under drought stress?

**Study B:** Soil water dynamics along the Kalahari dune transects in northern Namibia.

The objective of this study was to address the following questions:

- I. How does soil water dynamics differ across the three main topographic positions representative of the dune transects (dune crest, interdune and slope), particularly in terms of topsoil moisture retention, infiltration and surface water loss?
- II. To what extent do differences in soil water dynamics across dune topography determine interdune being the key hydrological accumulation zone under prevailing semi-arid conditions?

## **2. Effect of land management practices on soil water dynamics**

This study was conducted in two segments.

**Study C:** Soil water dynamics and yield responses of cowpea under conservation and traditional agriculture in northern Namibia.

The study aimed to investigate the following aspects:

- I. How do conservation agriculture and traditional agriculture as management practices influence soil water dynamics, particularly infiltration, evapotranspiration and soil water content under cowpea cultivation?
- II. To what extent does mulching, in combination with *Bradyrhizobium* inoculation improve crop yield?

**Study D:** Cowpea growth response to mulching and inoculation modifying soil water dynamics under simulated drought.

The objective of this study was to investigate two key questions:

- I. How do different types of mulching practices and rhizobial inoculation influence soil water dynamics in sandy soils under drought?
- II. Do these interventions translate into improved developmental performance in greenhouse-grown cowpea (*Vigna unguiculata*) under water stress?

### 3. Soil-plant-vapor interface

**Study E:** Water Vapor from deep soil reservoirs as a viable water source for plants in sandy soils.

The study aimed to address the following questions:

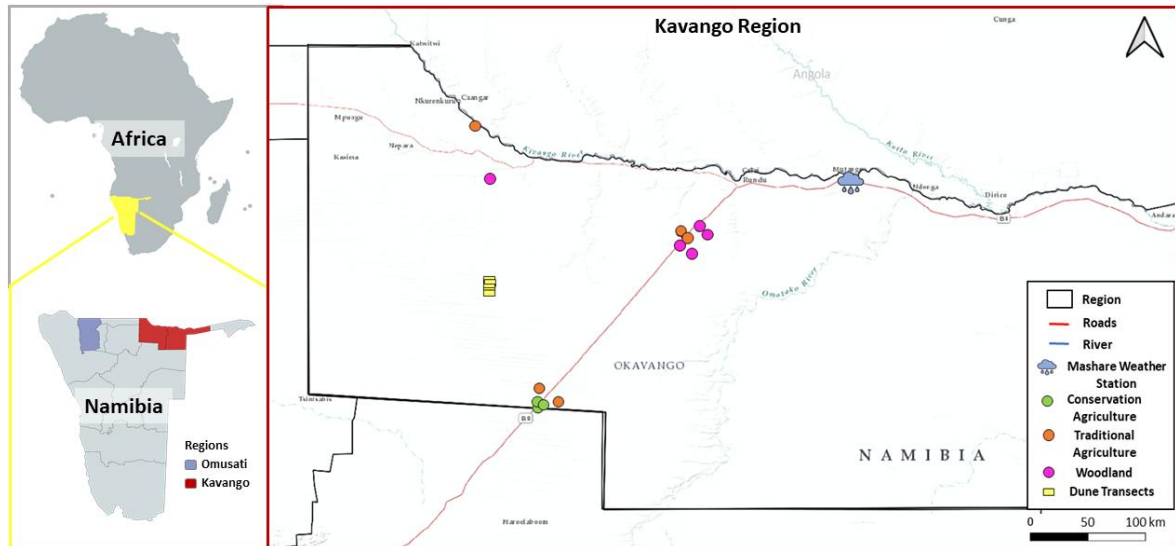
- I. Can plants take up water vapor from the hydraulically decoupled deep soil water reservoir?
- II. Does the utilization of water vapor have a physiological relevance to the plant survival under drought conditions?
- III. Can this process be enhanced by an agronomic management strategy, specifically, the application of mulch?

### Embedment Within Research Projects

This research was conducted as part of the SUSTAIN project (Sustainable resource management for improved resilience in sub-Saharan Africa), a collaborative initiative funded by the Bundesministerium für Forschung, Technologie und Raumfahrt (BMBFTR), in the framework of SASSCAL 2.0 (grant no. 01LG2051B) to strengthen research and innovation capacities in sustainable land management. The project integrates interdisciplinary approaches across hydrology, soil science, ecology and socio-economics to improve the understanding of resource dynamics in dryland systems. Within this framework, the present research contributes to the SUSTAIN work package on “Assessment of soil water conservation and soil water storage through conservation agriculture and stress tolerant legumes” focusing on the water related dimension of sustainability by analyzing soil water dynamics and plant-water interactions in Namibia’s sandy landscape. Additional support was provided through the CLICCS (Climate, Climatic Change and Society) funded by the Deutsche Forschungsgemeinschaft (DFG) under Germany’s excellence strategy, EXC 2037 CLICCS (390683824), as part of the University of Hamburg.

## 2 Material and Methods

### 2.1 Study Area



**Figure 2:** Map of Africa highlighting Namibia, and map of Namibia showing the Omusati and Kavango regions in the north. Extended map illustrates the investigated land-use sites and dune transects across the Kavango region ( $n = 5$ ).

Namibia, located within the semi-arid belt of sub-Saharan Africa, is characterized by pronounced climatic variability, recurrent droughts and strong seasonality that shape both land-use and vegetation dynamics (Harris et al., 2014; Moseki et al., 2025; Shiimi & Uchezuba, 2025). Namibia extends between latitudes 17°S and 29°S and longitudes 11°E and 25°E, covering an area of approximately 825,000 km<sup>2</sup> (Namibia, 2023) and is considered one of the most arid countries in sub-Saharan Africa (ANT, 2022). Namibia borders Angola to the north, South Africa to the south, Botswana to the east and Zambia in the northeast (Aikins, 2025). Large parts of the country are dominated by arid and semi-arid landscapes, with the Namib desert stretching along the Atlantic coast and the Kalahari Desert covering much of the eastern interior (ANT, 2022). Namibia's geographic position along the southwestern margin of the African continent exposes it to the influence of the cold Benguela current which stabilizes the lower atmosphere and suppresses rainfall, resulting in arid conditions despite high coastal humidity and frequent fog formation (WBG, 2021).

The Omusati region, located in north-central Namibia, forms part of the Cuvelai-Etoshia basin (Mendelsohn et al., 2013) and represents one of the country's most densely inhabited and intensively farmed areas (Hamalwa et al., 2025; NSA, 2023). The region lies between approximately 17°S and 18.5°S

latitude and 14°E and 16°E longitude, bordering Angola to the north (Figure 2) (ANT, 2022). Its topography is predominantly flat, with gentle slopes and shallow depressions formed by the ephemeral Cuvelai drainage system that channels seasonal floodwaters southwards toward the Etosha Pan (Hamutoko et al., 2018; Mapaure & Ndeinoma, 2011). The climate is semi-arid, with annual rainfall averaging between 350 and 500 mm, concentrated between November and April (Mendelsohn et al., 2000; Namibia Ministry of Regional Local Government, 2012; S. K. Awala et al., 2019). The prolonged dry season and frequent droughts result in a strong dependence on seasonal rains for crop cultivation and livestock watering (Angula & Kaundjua, 2016; Shiimi et al., 2023). Temperatures are high throughout the year, with summer maxima frequently exceeding 35°C and annual potential evapotranspiration rates surpassing rainfall inputs (Mendelsohn et al., 2013; Sheepo et al., 2025). Soils in Omusati are dominated by Arenosols and Calcisols of aeolian and fluvial origin (Mendelsohn et al., 2000; Munyebvu et al., 2018; Yoshinori et al., 2016), which are sandy to loamy-sand in texture (Bravo-García et al., 2025) with interbedded calcretes and silcretes overlying up to 300 m of variably cemented sands, clays and gravels (Wanke et al., 2014). These soils exhibit low organic matter content, limited nutrient availability and moderate acidity (Mumbi Chabala et al., 2022; Prudat et al., 2018). Agricultural production is mainly subsistence-based, focused on pearl millet and sorghum, supported by livestock grazing on communal rangelands (Newsham & Thomas, 2011). Water availability and soil fertility remain key limiting factors for productivity, making the region highly vulnerable to climate variability and land degradation (Iilonga & Ajayi, 2025; Mumbi Chabala et al., 2022).

The Kavango region, located in the northeast of Namibia (Figure 2), is densely populated and considered agriculturally active (Obeid & Mendelsohn, 2001). It extends along the Okavango river, which forms part of the border with Angola, between approximately 18°S and 20°S latitude and 19°E and 21°E longitude (ANT, 2022; Gaughan & Waylen, 2012). Elevations range between 1,050 and 1,150 meters above sea level, with gently undulating topography shaped by dune-interdune transects derived from Kalahari sand formations (David, 2021). Overall the landscape is dominated by dry woodlands, open savanna and smallholder agricultural fields, forming a mosaic of land-uses that reflect gradients in soil, vegetation, water dynamics and population growth (Gaughan & Waylen, 2012; Gröngröft et al., 2013a; Shiimi & Uchezuba, 2025; Uchezuba & Mbai, 2020). Over recent decades, population growth has accelerated agricultural expansion and woodland clearance, increasing pressure on the region's fragile sandy soils and natural resources (Mendelsohn, 2009).

Climatically, the Kavango region falls within the semi-arid tropical climate zone, with distinct wet and dry seasons (ANT, 2022). The rainy season typically extends from November to April, followed by a prolonged dry season from May to October (David, 2021). Long-term mean annual rainfall ranges spatially between 450 and 550 mm, with frequent drought years interrupting seasonal patterns (Awala et al., 2019; Matanyaire, 1997). Rainfall events are mostly convective and short in duration, often concentrated in a few intense storms with high spatial variability and localized distribution (Jury, 2013). Mean annual temperatures range between 22°C and 24°C, with summer maxima exceeding 35°C and winter minima occasionally dropping below 10 °C (David, 2021; Iortyom et al., 2022). The high potential evapotranspiration, often exceeding 2,000 mm per year, greatly surpasses rainfall inputs (IWA, 2018), resulting in a persistent soil water deficit. Wind patterns are dominated by easterly and northeasterly directions during the dry season (WBG, 2021), which enhance surface drying and contribute to aeolian sand transport (Garzanti et al., 2022b).

The soils of the Kavango region are predominantly classified as Arenosols (Gröngröft et al., 2013a; Strohbach & Petersen, 2007), derived from the extensive Kalahari sand formations that dominate much of northern and north-eastern Namibia (Pröpper et al., 2010). These soils are characterized by their coarse texture, weak aggregation and extremely low content of organic matter and clay typically less than 5% (ANT, 2022). The profile development is minimal, with a uniform sand matrix extending to several meters in depth and a lack of distinct horizons (EIS, 2000; Gröngröft et al., 2013a). The soils are coarse-textured, have extremely high infiltration rates and low water holding capacity (Mendelsohn, 2009). Due to the high infiltration rates in sandy soils, much of the rainfall percolates quickly beyond the rooting zone, resulting in only short-lived increases in soil moisture and limited water availability for plants (Räsänen et al., 2020). Under the region's semi-arid conditions, evaporation from the soil surface is also high, further reducing water retention (Wang et al., 2007). In addition to these hydrological limitations, the soils exhibit poor nutrient retention due to rapid drainage and prevailing low cation exchange capacity (Vushe et al., 2016). As a result, nitrogen and phosphorous are readily leached during intense rainfall storms, reducing their availability to plants (Vushe & Amutenya, 2019; WBG, 2021). The soils are typically acidic, with pH values ranging from 4.5 to 6.0 and are deficient in essential macro- and micronutrients (Pröpper et al., 2010; Strohbach & Petersen, 2007). Local topography, defined by dune-interdune systems, introduces additional spatial variability (Pröpper et al., 2010), where, dunes tend to be excessively drained, whereas interdunes may temporarily accumulate water and fine material (Garzanti et al., 2022b), allowing slightly higher fertility and vegetation density (Gröngröft et al., 2013b).

## 2.2 Study Design

### 2.2.1 Land-Use Systems of the Kavango Region of Namibia



**Figure 3:** Representative photographs of the investigated land-use sites showcasing from left to right, conservation agriculture field with pearl millet crops arranged in rows along with faded riplines and sparse residue cover. Traditional agriculture field showcasing bare sandy surfaces, highly tilled soil and scattered crop stands. Near-natural woodland sites dominated by shrubs and broad-leaved trees. Pictures by Sekhri S. (2024)

#### Conservation Agriculture

The conservation agriculture fields investigated in the Kavango region had been managed under reduced tillage for more than six consecutive years (Figure 3), incorporating the use of shallow riplines as planting furrows (Kudumo et al., 2025; Mudamburi et al., 2018), partial soil cover with organic materials or crop residue (Mhlanga et al., 2021) and crop rotations (Shiimi & Uchezuba, 2025). The farmlands followed a rotation between cowpea and pearl millet, as promoted through regional agricultural development programs (UNDP, 2010). During the 2023 growing season, cowpea was cultivated, followed by pearl millet in 2024. All study sites were selected in collaboration with the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), which has supported conservation agriculture implementation and farmer engagement in the region. Mulching practices were part of the conservation agriculture framework, however, during field visits, only limited surface cover was observed (March 2024). Farmers generally relied on post-harvest residues and dry grasses for mulch, which were often sparse due to livestock grazing and competing household uses. The shortlisted conservation agriculture farmlands therefore represented smallholder subsistence farming conditions, long-term reduced tillage systems with minimal soil disturbance, partial residue cover and alternating legume-cereal rotations established under semi-arid climatic constraints. Soil properties are detailed in Table 1.

## Traditional Agriculture

Traditional agriculture in the Kavango region is primarily a rainfed subsistence farming system (Mendelsohn, 2009). The investigated traditional agriculture fields (Figure 3) were selected as representative sites of the region's typical traditional land-use practices. These fields were managed using conventional tillage using animal-drawn ploughs or harrows with high draft power to prepare the soil before planting (Siyambango et al., 2022). The soil surface was left bare, with no visible residue retention or mulch cover following harvest (Shiimi, 2025). Cropping systems were dominated by monocultures of pearl millet, reflecting the limited diversification typical of smallholder subsistence systems in northern Namibia (Shiimi & Uchezuba, 2025; Zegada-Lizarazu et al., 2007). Planting was done manually, often by scattering seeds or placing them irregularly in the tilled soil without a defined row structure (Shiimi, 2025; Spear & Chappel, 2018). Tillage depth varied depending on the availability of draft power and soil conditions but generally resulted in complete soil inversion, exposing the soil surface to rapid drying under high temperatures (Misika & Mwenya, 1999; Mudamburi et al., 2018). These selected farmlands therefore represented the prevailing traditional land-use practices, where production remains fully dependent on seasonal rainfall and minimal external inputs.

## Woodland

The woodland sites, located alongside agriculture fields, served as near-natural reference areas within community forest zones in the Kavango region (Figure 3). These woodlands represented minimally disturbed savanna system dominated by a mixture of woody species, shrubs and grasses, with limited grazing pressure and no recent signs of cultivation (Strohbach & Petersen, 2007). Vegetation structure was heterogeneous, typically composed of broad-leaved tree species such as *Baikiaea plurijuga*, *Pterocarpus angolensis* and *Burkea africana*, interspersed with perennial grasses and scattered shrubs (Burke, 2006; Wingate et al., 2016). The ground surface was largely covered by litter and grass residues, which reduces direct evaporation and protects the soil against erosion (Chidumayo & Gumbo, 2010). Soils in these areas exhibited loose sandy textures similar to adjacent farmlands but maintained higher organic matter and biological activity due to the continuous input of plant residues and minimal mechanical disturbance (Archer, 2018; de Blécourt, 2018). These sites were selected to represent near-natural conditions against which the soil water dynamics of cultivated systems could be compared.

Site selection for conservation agriculture, traditional agriculture and woodlands was guided by local expertise and farmer interactions facilitated through a GIZ representative. Fields were selected as representative examples of each land-use type based on their consistent management history and alignment with typical regional practices. The sites were visited to verify management conditions and field maintenance, ensuring comparable soil types across locations. For each land-use system, five sites were selected, however, one of the conservation agriculture sites was later excluded after a 2024 field visit revealed that the field had been converted for housing and no longer existed under cultivation.

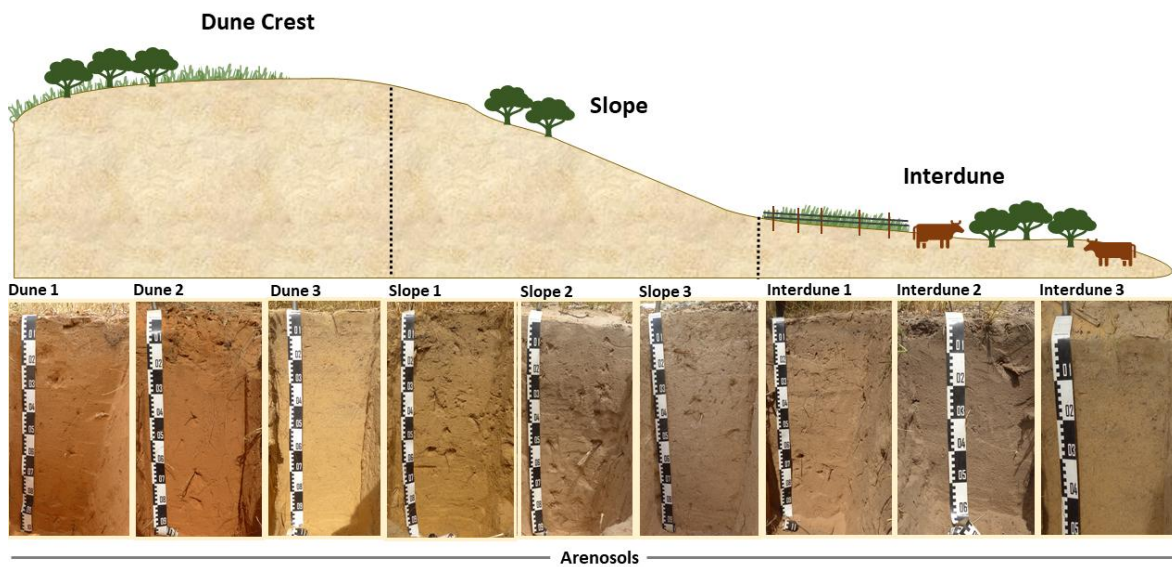
**Table 1:** Soil properties of different land-use systems at 0-10 cm soil depth (n=5\*).

<b>Properties</b>	<b>CA</b>	<b>TA</b>	<b>W</b>
BD (g/cm <sup>3</sup> )	1.57 ± 0.02	1.58 ± 0.05	1.53 ± 0.03
WHC%	28.70 ± 1.06	28.26 ± 1.36	31.16 ± 1.00
SOC%	0.19 ± 0.02	0.19 ± 0.06	0.50 ± 0.05
C/N	12.54 ± 1.03	12.56 ± 3.67	17.15 ± 2.18
pH (H <sub>2</sub> O)	6.55 ± 0.17	6.57 ± 0.35	5.71 ± 0.24
Sand%	91.73 ± 0.64	93.66 ± 3.09	96.67 ± 0.77

Here, CA: Conservation Agriculture, TA: Traditional Agriculture, W: Woodland, BD: Bulk Density, WHC: Water Holding Capacity, SOC: Soil Organic Carbon and C/N: Soil Organic Carbon by Total Nitrogen Ratio, \*n = 5 for TA and W; n = 4 for CA.

## 2.2.2 Geomorphology of Dune Transects

The linear dunes embedded within the characteristic Kalahari landscape (Jolivet et al., 2022; Lancaster, 1981) encompass a sequence of topographic positions (Thomas & Wiggs, 2022) namely the dune crest, slope (flanks) and interdune depressions that form a longitudinal dune-interdune transect (Pröpper et al., 2010; Stone et al., 2022). The dune ridges, trending roughly east-west or more specifically northeast-southwest in the Kavango region, typically stand few meters above interdune lows (local relief varies with landscape age) and are remnants of Holocene to late Pleistocene aeolian activity stabilized under increasing vegetation cover (Garzanti et al., 2022b; Lancaster, 1988; Thomas & Shaw, 1991; Wang et al., 2007). Over time, wind driven sand transport (saltation) has built the dune crest ridges, while finer materials and occasional overland flow deposit in interdune troughs, gradually smoothing sharp relief (Thomas & Leason, 2005).



**Figure 4:** A dune transect illustration depicting three topographic positions, dune crest, slope and interdune. Soil profiles showcase Arenosols with uniform sandy texture and weak horizon development typical of Kalahari dunes, with subtle color and structure variations (Illustration by Sekhri S., Profile pictures by Sekhri S & Gröngröft A. 2024).

These dunes are composed of deep, coarse to fine aeolian sands (Thomas & Wiggs, 2022), with little vertical differentiation (i.e. weak or absent pedogenic horizons, Figure 4) and very high permeability typical of Kalahari sands, which strongly influence soil water dynamics (Stone et al., 2022). Dune crests usually exhibit reddish sand colors due to higher iron oxide content, whereas, lower slopes and interdunes have paler, greyish sands (Thomas & Wiggs, 2022). Erosion and redeposition over millennia have generated a generally homogeneous sand matrix with locally finer grain infilling in interdunes (Garzanti et al., 2022b). On dune crests, vegetation is often sparse, dominated by grasses and small shrubs, on the lower slopes and in interdunes moisture accumulates more readily, permitting denser growth of woody seedlings, shrubs and seasonal grasses (Burke, 2002; Pröpper et al., 2010). The interdunes may also intermittently retain shallow ponding or elevated soil moisture after intense rainfall, supporting localized increased fertility (Burrough et al., 2015), seed germination and vegetation densification (Jolivet et al., 2022; Wiggs et al., 1995).

Although these dunes are now largely stabilized by vegetation, subtle microtopographic textures remain visible (e.g. faint crest ridgelines, slope gradients and interdune hollows), indicating their geomorphic heritage (Jolivet et al., 2022; McFarlane et al., 2005). From a hydrological perspective, these dune transects provide a potential to investigate natural gradients in soil water dynamics across their sandy terrain. As infiltration and water retention in sandy soils are strongly influenced by local topography, variations across dune crests, slopes and interdunes are expected to produce distinct patterns of soil moisture

distribution. During the 2024 field campaign, three representative dune transects were selected based on their location, geomorphic similarity and accessibility to ensure comparability among sites. Soil properties are detailed in Table 2.

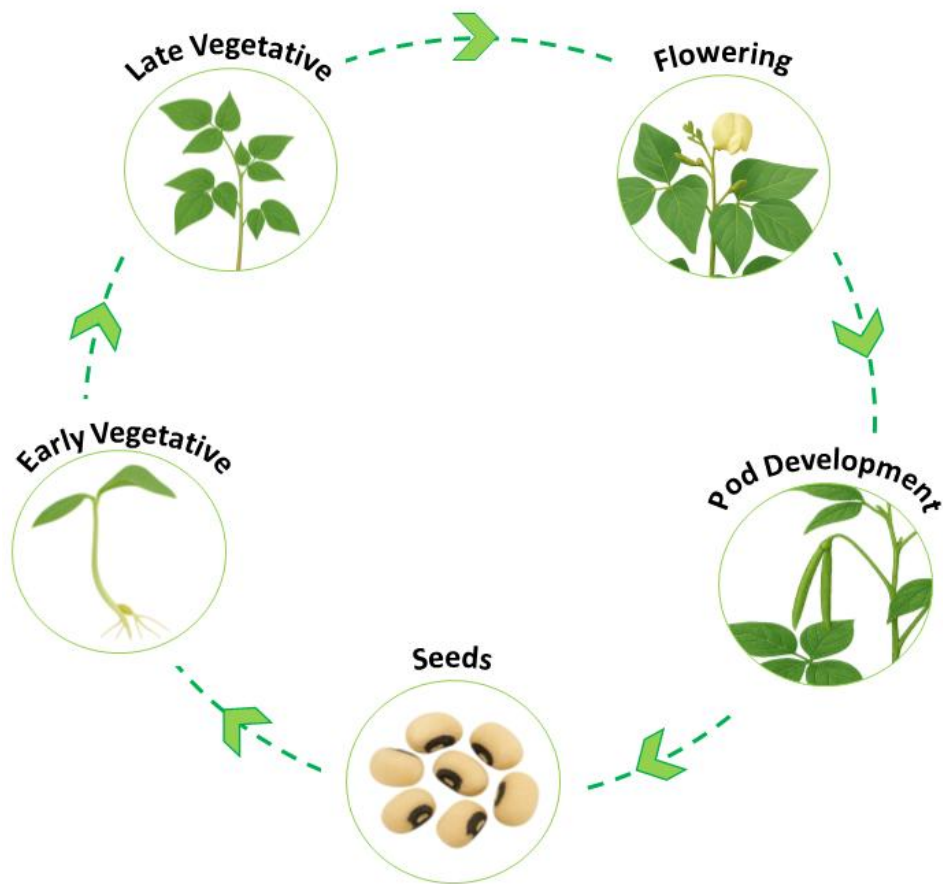
**Table 2:** Soil properties of dune toposequence at 0-10 cm soil depth (n = 3).

<b>Properties</b>	<b>Dune Crest</b>	<b>Slope</b>	<b>Interdune</b>
BD (g/cm <sup>3</sup> )	1.55 ± 0.02	1.56 ± 0.01	1.58 ± 0.02
FC%	14.27 ± 4.24	16.09 ± 0.99	14.20 ± 3.39
Porosity (vol%)	41.49 ± 0.78	41.25 ± 0.58	40.25 ± 0.58
SOC%	0.22 ± 0.06	0.21 ± 0.04	0.24 ± 0.04
C/N	9.32 ± 1.55	8.18 ± 0.98	10.31 ± 0.18
pH (H <sub>2</sub> O)	5.76 ± 0.06	5.48 ± 0.23	5.94 ± 0.39
Sand%	96.30 ± 0.22	95.88 ± 0.88	95.26 ± 2.26

Here, BD: Bulk Density, FC: Field Capacity, SOC: Soil Organic Carbon and C/N: Soil Organic Carbon by Total Nitrogen Ratio. Retention curves are given in Appendix.

### 2.2.3 Cowpea (*Vigna unguiculata*) as a Model Agricultural Crop

Cowpea is a legume increasingly integrated into dryland farming systems for its drought tolerance ability and short life cycle (Figure 5) (Becker et al., 2024; Jeong et al., 2025). Originally introduced to Namibia as part of climate-resilient crop initiatives, it adapts well to sandy, low-fertility soils where other crops fail, owing to its quick establishing root system and efficient water use (Ezin et al., 2021; Ritte et al., 2022). As a rotation crop, cowpea improves soil fertility through symbiotic nitrogen fixation, replenishing nutrient depleted soils and reducing the need for synthetic fertilizers (Kyei-Boahen et al., 2017; Martins et al., 2003). Its rapid growth, typically completing a full cycle within 70-90 days makes it suitable for short rainy seasons common in northern Namibia (de Souza Silva et al., 2024; Tankari et al., 2021). Agronomically, cowpea contributes to sustainable land management by enhancing ground cover, minimizing soil erosion and stabilizing soil aggregates in sandy terrains (de Blécourt et al., 2019; de Souza Silva et al., 2024). Nutritionally, it is valued for its high protein, mineral and carbohydrate content, providing an affordable dietary source of nutrition in semi-arid communities (Ahmed & Suliman, 2010; Ezin et al., 2021). These combined agronomic and nutritional traits make cowpea a strategic crop for strengthening food security and soil health under Namibia's increasingly variable climatic conditions (Jeong et al., 2025; Ritte et al., 2022).

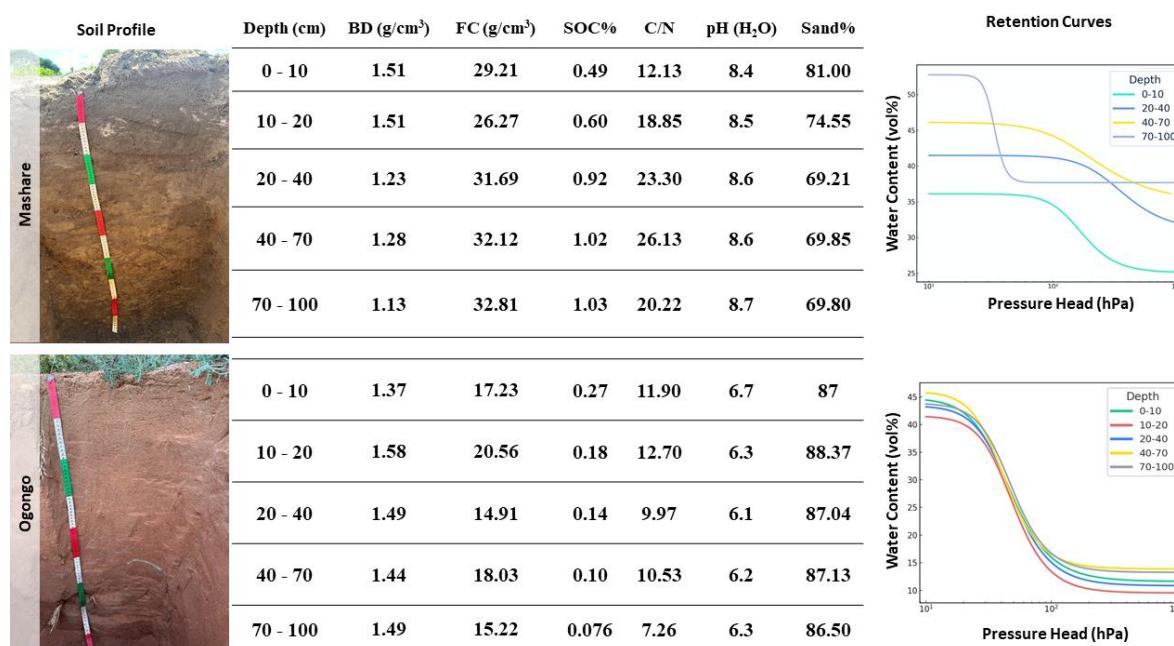


**Figure 5:** Cowpea life cycle showcasing developmental progression including early vegetative, late vegetative, flowering to pod initiation and development stages (Illustrations created with OpenAI's DALL·E, diagram compiled and designed by Sekhri S.).

#### 2.2.4 Mashare and Ogongo Experimental Field Sites

The Mashare site is situated in Mashare Agricultural Development Institute (MADI) in the north-eastern Kavango region of Namibia, at an altitude of about 1068 m above sea level (S 17° 53' 27"; E 20° 10' 17"), within an old floodplain of the Okavango river (Becker et al., 2024). The region is characterized by a semi-arid climate with mean annual precipitation of 571 mm (Gröngröft et al., 2013a), occurring mainly from November to March and mean annual temperatures between 22 and 26°C, with maximum daily temperatures frequently exceeding 35°C during summer months (Huber et al., 2022). The soils consist mainly of fine sandy material with thin interlayers of silt and clay that originate from the past fluvial deposits (Gröngröft et al., 2013b; Jolivet et al., 2022) and are classified as Luvisols (Arenic) (Becker et al., 2024). These soils exhibit coarse texture, slight acidity, low cation exchange capacity, low clay and organic matter contents (Figure 6).

The Ogongo site, located in the Omusati region of northern Namibia, lies on slightly elevated Kalahari sand terraces that are occasionally influenced by runoff from the Angolan highlands (Jolivet et al., 2022; Jürgens et al., 2012). The Omusati region is characterized by low and highly variable rainfall and persistently high temperatures throughout the year (Iilonga & Ajayi, 2025; Sheepo et al., 2025). Soils in this region are predominantly derived from the old Kalahari parent sands overlaying hardpan or shallow lithic substrates, with occasional clay or silt deposits occurring in depressional or flood influenced topographies (Arendt et al., 2023; Kangombe, 2010). The soil from Ogongo, classified as Eutric Sideralic Arenosol (Becker et al., 2024), exhibits a loose sandy texture with minimal horizon development, low organic carbon content and a neutral to slightly acidic pH (ANT, 2022; Prudat et al., 2018). Soil fertility is uniformly low, with poor cation exchange capacity, limited nutrient reserves and minimal organic matter accumulation under continuous cultivation. The soil used in this study was collected from the experimental field situated at the University of Namibia agricultural campus (S 17°41'08.9"; E 15°18'01.1"). The detailed physical and chemical properties of the soil, including soil water retention characteristics are presented in Figure 6.



**Figure 6:** Mashare and Ogongo soil profiles with detailed soil physical and chemical properties. BD: Bulk Density, FC: Field Capacity, SOC: Soil Organic Carbon and C/N: Soil Organic Carbon by Total Nitrogen ratio.

The experimental plots built at Mashare and Ogongo study site were prepared following traditional and conservation agriculture management practices (Figure 7). Under conservation agriculture, ox-drawn riplines were made and wheat

straw mulch was applied to the soil surface, while traditional agriculture plots were tilled with a high draft power tractor and maintained without soil cover. A fresh culture of *Bradyrhizobium* strain 1–7 (Mashare) and 26-nodO (Ogongo) was used as the inoculant and applied to cowpea seeds before sowing. For this dissertation, only the Mashare study site was investigated in the field, while soils collected from the Ogongo site were used for the greenhouse experiment.



**Figure 7:** Experimental layout of the fields at Mashare and Ogongo. Conservation agriculture and traditional agriculture management, with treatments including; - Inoculant (no inoculation), + Inoculant (with inoculation) and + N Control (nitrogen-fertilized). Conservation agriculture plots further divided by mulch presence or absence. Plot numbers correspond to specific field identifiers. Si denotes the Silwana and Na the Nakare cowpea variety. Yellow empty boxes showcase unplanted plots in each treatment category.

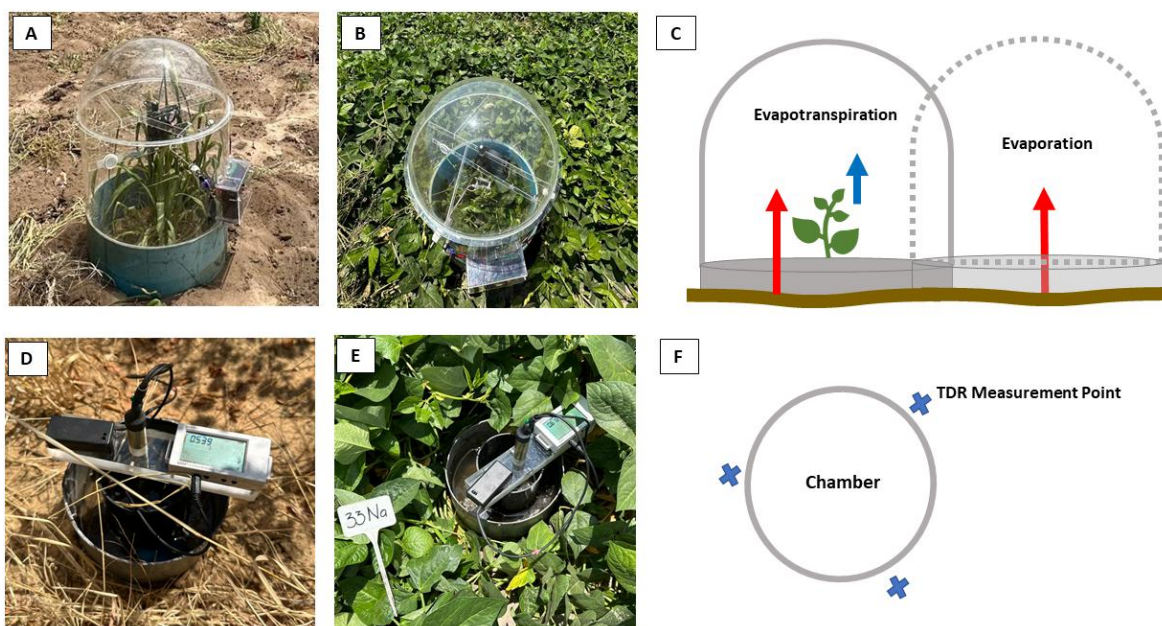
## 2.2.5 Field Work, Measurements and Analysis

**Table 3:** Overview of field methods conducted for this dissertation.

Location	No. of Sites	Variables Measured	Methods	
<b>Study A: Investigating soil water dynamics to improve agriculture: Namibian land-use systems under drought</b>				
CA smallholder farmlands	5*	ET; Inf; SWC	Closed Chamber (ET) → 3x per day per site, replicated on 3 separate days under consistent weather conditions;	
TA smallholder farmlands	5			
Woodland	5	Inf; SWC	Infiltration (Inf) → 5x per site; TDR (SWC) → 3x per chamber measurement	
<b>Study B: Soil water dynamics along the Kalahari dune transects in northern Namibia</b>				
Dune crest	3	ET; Inf; SWC	Closed Chamber (ET) → 3x per day per site, replicated on 3 separate days under consistent weather conditions;	
Slope	3			
Interdune	3			
<b>Study C: Soil water dynamics and yield responses of cowpea under conservation and traditional agriculture in northern Namibia</b>				
Treatments	No. of Plots	Variables Measured	Methods	
CA-I+M	4	ET; Inf; SWC	Closed Chamber (ET) → 1x per day per plot, replicated on 2 separate days under consistent weather conditions;	
CA-I-M	4			
CA+I+M	4			
CA+I-M	4			
CA+N	4			
TA+I	4			Infiltration (Inf) → 3x per treatment;
TA-I	4			TDR (SWC) → 3x per chamber measurement
TA+N	4			
Un	4			

CA: Conservation Agriculture; TA: Traditional Agriculture; \*Out of five selected sites for conservation agriculture four were investigated, as the 5<sup>th</sup> site was destroyed before field visit in 2024. ET: Evapotranspiration; Inf: Infiltration; SWC: Soil Water Content; TDR: Time Domain Reflectometry soil moisture sensor; +M: Mulched; -M: Without Mulch; +I: Inoculated; -I: No Inoculation; +N: Nitrogen- fertilized; Un: Unplanted.

## Closed Chamber Method, Infiltration and Soil Water Content Measurements



**Figure 8:** Field-based measurements showcasing closed chamber setup enclosing a single pearl millet (A) and cowpea plant (B). Illustration depicting evapotranspiration (with plant) and evaporation (bare soil) measurements (C). Double-ring infiltrrometer setup with integrated pressure sensor (D-E). Illustration showcasing soil water content measurement points around the chamber collar (top view, F). Illustrations and pictures by Sekhri S.

**Evapotranspiration** was measured using a closed-chamber technique designed to capture short-term water vapor fluxes under field conditions (Reicosky & Peters, 1977; Stannard, 1988). The chamber was constructed from UV-transmissive plexiglass in a hemispherical shape (49 cm diameter, 56 cm height) and mounted onto cylindrical PVC collars (49 cm diameter, 20 cm height, 5 mm wall thickness) inserted into the soil before measurement (Figure 8A-C). The soil around each collar was compacted to minimize lateral gas exchange and ensure that water vapor flux originated solely from the enclosed soil-plant system (Bonhold, 2021). The chamber was equipped with sensors for air temperature ( $^{\circ}\text{C}$ ), relative humidity (%), barometric pressure (hPa) and incoming solar radiation ( $\text{W m}^{-2}$ ), all connected to an Arduino based datalogging system that recorded data at three second intervals (Macagga et al., 2024). A small internal fan maintained uniform air circulation and prevented water vapor stratification (Reicosky & Peters, 1977). Measurements were conducted under stable weather conditions, with each chamber enclosing a single representative plant. For each site, three replications were conducted on the same day to obtain a representative mean value and this procedure was repeated on separate days. These measurements were performed across land-use systems including

conservation agriculture, traditional agriculture, woodland and dune transects encompassing the crest, slope and interdune positions. On the experimental fields at Mashare, one measurement was carried out per plot and repeated on two separate days, with each chamber enclosing one cowpea plant. Changes in absolute humidity within the chamber over time were used to compute evapotranspiration rates ( $\text{mm h}^{-1}$ ) via the Magnus equation, from which saturation vapor pressure and vapor pressure deficit were derived (Junzeng et al., 2012). The calculation sequence (Equations 1-6) involved determination of the saturated vapor pressure, uncorrected vapor pressure and vapor density from temperature ( $^{\circ}\text{C}$ ), relative humidity (%) and air pressure (hPa) data recorded during chamber measurements.

Saturation vapor pressure was computed using the given Magnus Equation,

$$\text{SVP} = 6.11 * e^{((17.62 * T) / (242.12 + T))} \quad \text{Equation 1}$$

Where, SVP is the Saturation Vapor Pressure (hPa) and T is the air temperature ( $^{\circ}\text{C}$ ) at each timestep.

The uncorrected vapor pressure (VPu, in hPa) was calculated as,

$$\text{VPu} = \text{SVP} * (\text{RH} / 100) \quad \text{Equation 2}$$

Where, RH is the relative humidity (%) at each timestep.

The corresponding uncorrected vapor density (VDu, in  $\text{kg m}^{-3}$ ) was obtained from,

$$\text{VDu} = (\text{VPu} * 100) / (461.51 * (273.16 + T)) \quad \text{Equation 3}$$

Here, the universal gas constant ( $461.51 \text{ J kg}^{-1} \text{ K}^{-1}$ ) is included.

To correct for air pressure effects, vapor density was adjusted according to,

$$\text{VDc} = (1.0016 + (3.15 * 10^{-6}) * (P * 100) - (0.074 / P * 100)) * \text{VDu} \quad \text{Equation 4}$$

Where, VDc is the corrected vapor density ( $\text{kg m}^{-3}$ ) and P is pressure (hPa).

The rate of change in vapor density over time (slope = m) was derived through linear regression of VDc against time (s), which provided the water flux (WF) as the following,

$$\text{WF} = (m * (V_{\text{ch}} + V_{\text{co}})) / A \quad \text{Equation 5}$$

Where, WF is the water flux ( $\text{kg m}^{-2} \text{ s}^{-1}$ ), m is the regression slope ( $\text{kg m}^{-2} \text{ s}^{-1}$ ),  $V_{\text{ch}}$  is the volume of the chamber ( $0.0955 \text{ m}^3$ ),  $V_{\text{co}}$  is the volume of the collar ( $0.0283 \text{ m}^3$ ) and A is the area ( $0.1886 \text{ m}^2$ ).

Water flux values were successively converted to equivalent evapotranspiration rates (ET in mm h<sup>-1</sup>) by unit conversions with,

$$ET = (WF*10^6*3600)/10^6 \quad \text{Equation 6}$$

This approach allowed quantification of total evapotranspiration as the combined soil evaporation and plant transpiration flux within the enclosed chamber system under field conditions.

**Infiltration** measurements were conducted using a double-ring infiltrometer to quantify vertical water movement into the soil under field conditions (Maheshwari, 1996). The instrument consisted of two concentric stainless-steel (outer) and PVC (inner) rings, with inner and outer diameters of 30 and 60 cm, respectively, inserted few centimeters into the soil surface (Figure 8D-E). Water was poured simultaneously into both rings to maintain equal head levels, ensuring that vertical infiltration dominated over lateral flow (Gregory et al., 2005; Li et al., 2019). Water levels were recorded at one second intervals using a customized pressure sensor connected to a datalogger, allowing continuous monitoring of the infiltration process. To capture spatial variability, five replicate measurements were performed at each land-use site including conservation agriculture, traditional agriculture, woodland along with dune transects including the dune crest, slope and interdune positions. For Mashare experimental field, three infiltrations were performed for each treatment.

Infiltration rates (mm h<sup>-1</sup>) were calculated based on the decline in water level within the inner ring over time (Eqs. 7-10). The initial step involved determining the height of the water column (h) at the start of the measurement from the voltage-depth relationship of the pressure sensor. This was derived using the linear calibration function as given in the following,

$$H = (U_s - U_e)/m \quad \text{Equation 7}$$

where,  $U_s$  and  $U_e$  represent the starting and ending voltages (mV), respectively.  $m$  is the regression slope of the calibration curve (0.0109 V cm<sup>-1</sup>) and  $h$  the height of the water column (cm).

The infiltrated water volume during each time interval was then obtained from the product of the infiltration area and the measured height as given in the following,

$$V = A*h \quad \text{Equation 8}$$

where,  $V$  is the volume (cm<sup>3</sup>) and  $A$  is area (86.5901 cm<sup>2</sup>).

The infiltration rate ( $I$ ) in cubic centimeters per second was computed as the following,

$$I = V/t \quad \text{Equation 9}$$

With,  $t$  being the elapsed time (s).

Finally, the infiltration rate was converted into comparable hydrological units ( $\text{mm h}^{-1}$ ) using the following,

$$I_c = (I/A)*3600*10 \quad \text{Equation 10}$$

Where,  $I_c$  denotes the converted infiltration rate ( $\text{mm h}^{-1}$ ). This calculation sequence enabled direct comparison of infiltration performance across land-use systems by expressing infiltration as standardized flux per unit of surface area.

**Soil water content** was measured using a Time Domain Reflectometry (TDR) soil moisture sensor with three 10 cm rods (Filintas, 2025; Maisha et al., 2025). The sensor was inserted in the soil adjacent to the chamber collar to capture near-surface moisture conditions representative of the evaporation zone (Figure 8F). For each chamber measurement, three independent readings were taken around the collar to account for spatial variability and averaged to obtain a representative soil moisture value. Measurements were performed simultaneously with evapotranspiration recordings to ensure comparable environmental conditions.

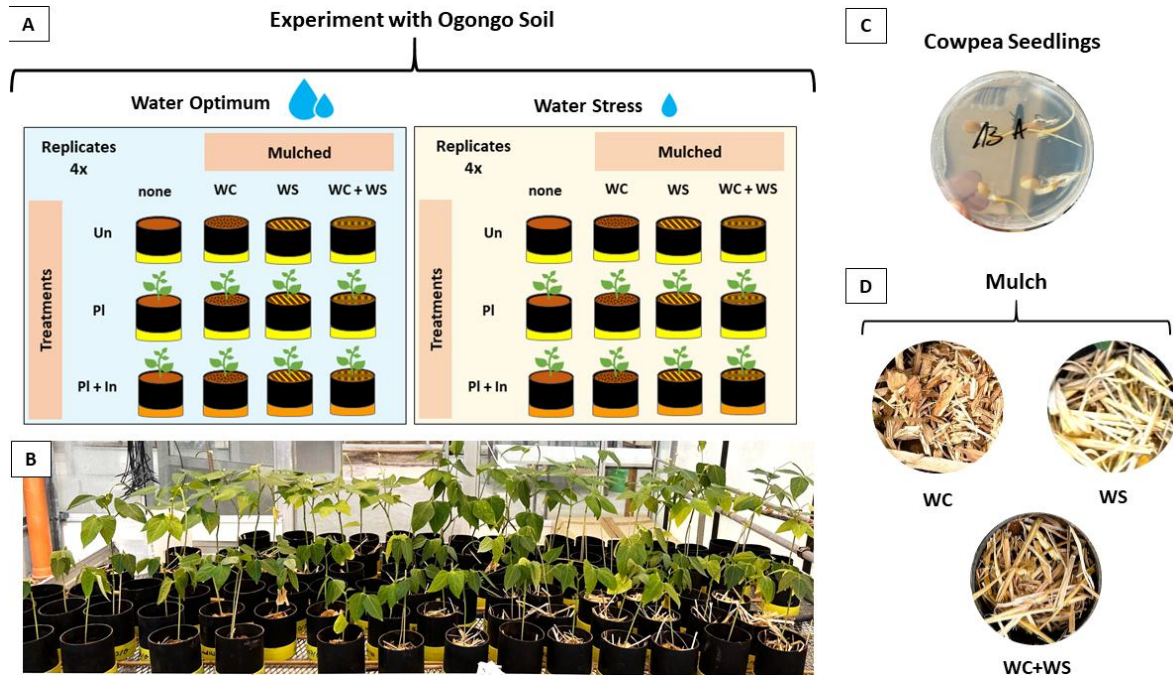
## 2.2.6 Laboratory Experiments, Measurements and Analysis

**Table 4:** Overview of laboratory experimental methods conducted for this dissertation.

Treatments	Replicates	Variables Measured	Methods
<b>Study D: Cowpea growth response to mulching and inoculation modifying soil water dynamics under simulated drought</b>			
Un	4	Evaporation	Soil → From Ogongo study site; Water levels → Water optimum (45% of max. WHC) and Water stress (20% of max. WHC); Evaporation (pot weighting) → measured every 5th day;
Un+WC	4		
Un+WS	4		
Un+WC+WS	4		
PI	4	Evaporation; cowpea physiology; cowpea developmental stages; root, shoot and pod biomass	Plant physiology → measured every 10th day; Biomass → after harvest (day 84) Composite score modelling was done based on water optimum growth threshold
PI+WC	4		
PI+WS	4		
PI+WC+WS	4		
PI+In	4		
PI+In+WC	4		
PI+In+WS	4		
PI+In+WC+WS	4		
<b>Study E: Water vapor from deep soil reservoirs as a viable water source for plants in sandy soils</b>			
Treatments (Experiment 1)			
C (PI)	3	$\delta^2\text{H}$ tracing and signal strength; Evaporation from source water reservoir	$\delta^2\text{H}$ → Cryogenic water extraction & Isotopic water analysis; Evaporation → Weighting water reservoir before and after the experiment
Un	3		
Un+M	3		
PI	3		
PI+M	3		
Treatments (Experiment 2)			
PI-V	3	Plant survival (time period); Evaporation from source water reservoir; plant biomass	Plant survival → Number of days (till wilting point, visual confirmation); Evaporation → Weighting water reservoir before and after the experiment; Biomass → Weighting saplings before and after the experiment
PI+V	3		
PI+M-V	3		
PI+M+V	3		

Un: Unplanted; PI: Planted; WC: Wood Chips; WS: Wheat Straw; WHC: Water Holding Capacity; C (PI): Control Treatment With Plants; +V: With Water Vapor Source; -V: Without Water Vapor Source.

## Greenhouse Pot Experiment Setup and Measurements



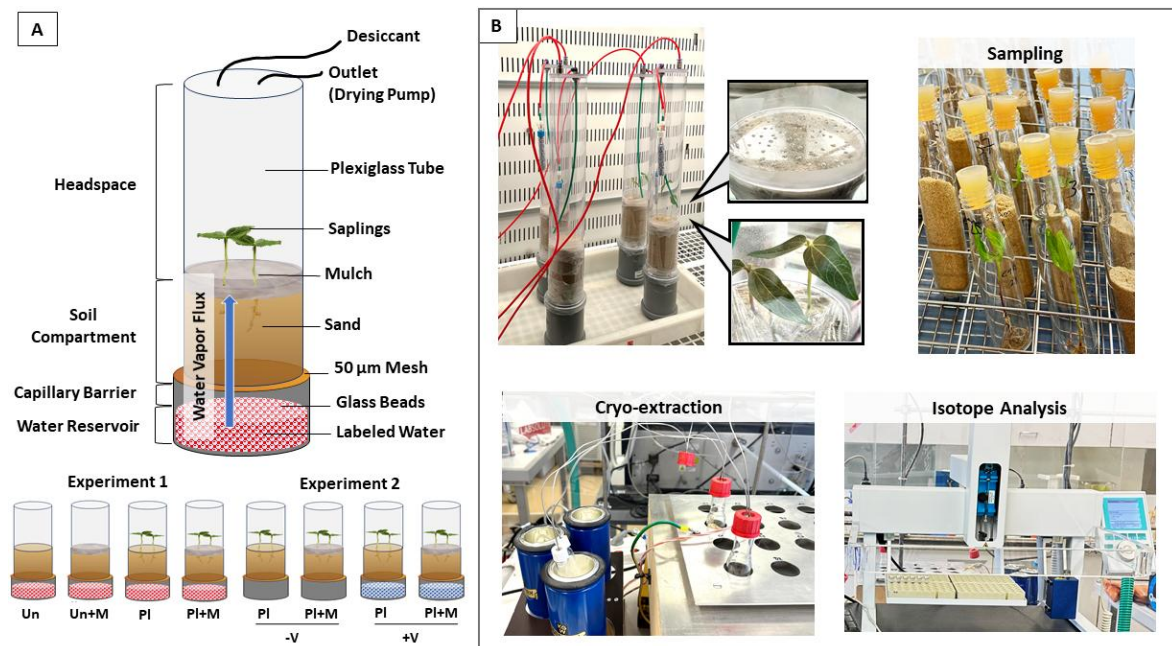
**Figure 9:** A. Experimental study design of the greenhouse pot experiment with two water levels; water optimum and water stress, three planting treatments; unplanted (Un), planted (PI) and planted+inoculated (PI+In) and four mulching categories; none, wood chips (WC), wheat straw (WS) and a 1:1 mixture (WC+WS). B. Experimental pots with water stress replicates in front and water optimum at back. C. Cowpea seedlings (2-3 days old) in agar plates. D. Mulching materials. Illustrations and pictures by Sekhri S.

To evaluate the effect of conservation agriculture management practices in a controlled setting, a greenhouse pot experiment was established. Mulching as a soil management practice, used as a soil cover, was studied in combination with the synergistic effects of rhizobial inoculation. The experiment included soils collected from Ogongo study site, comprised two irrigation regimes 45% of maximum water holding capacity (water optimum) and 20% of maximum water holding capacity (water stress), three planting treatments including unplanted, planted and planted+inoculated with four mulch categories (no mulch, wheat straw, wood chips and a 1:1 combination of both material) and cowpea plants (Figure 9).

Analysis included evaporation measurements carried out every fifth day to estimate soil water loss. Plant physiological parameters, including number of leaves, nodes and stem height, were recorded every tenth day to monitor plant development. At maturity, plants were harvested, separated into shoot and root components and oven dried at 60°C to determine dry biomass. Derived indices, including water use efficiency, transpiration efficiency, pod transpiration efficiency and harvest index were calculated to assess treatment performance

under optimum and water stress conditions. To further evaluate the influence of water stress on reproductive progression, a composite score model was applied to quantify delays in pod initiation across water stress treatments. This experimental design enabled comparison of how mulching, inoculation and water availability jointly affected cowpea growth and its physiological adaptation under simulated drought stress.

## Water Vapor Experimental Setup, Cryo-Extraction and Isotopic Analysis



**Figure 10:** A. Soil-plant-vapor experimental study design showcasing a plexiglass column with labeled water reservoir, capillary barrier, soil compartment and headspace with planted *Vigna radiata* saplings. Treatments include; unplanted (Un), unplanted + mulched (Un+M), planted (PI), planted+mulched (PI+M), without vapor source (-V) and with vapor source (+V). B. Laboratory setup showcasing treatment columns in a poly climatic chamber, sampling, cryogenic vacuum extraction of water and isotope analysis. Illustrations and pictures by Sekhri S.

A controlled column experiment was established using custom-built plexiglass columns to examine water vapor movement from a deep soil water reservoir to plants under extreme drought conditions (Figure 10). Each column consisted of a bottom water reservoir, an air-filled capillary barrier (~3 cm) and a root barrier (50 µm nylon mesh) to permit only water vapor diffusion. The reservoir contained deuterium-enriched water, serving as an isotopic tracer. The soil compartment was filled with washed sea sand and maintained under a controlled diurnal temperature regime of 30°C day and 15°C night. Four treatments were established; unplanted, planted, unplanted + mulched and planted + mulched, with a control planted column containing unlabeled water. Plastic food wrap was

used as mulch. Each treatment was replicated three times. After seven days, column components were sampled for isotopic analysis. Additionally, a separate set of planted and mulched columns with and without the vapor source was used to evaluate the physiological relevance of water vapor uptake (plant survival).

Water from soil, plant and water vapor condensate samples was extracted using cryogenic vacuum distillation, a method that ensures efficient water recovery while preventing isotopic fractionation during heating (Aragufis-Aragufis et al., 1995; Koeniger et al., 2011). Samples were placed in glass extraction tubes and heated to 130°C under vacuum conditions, allowing water to vaporize and subsequently condense in liquid nitrogen cooled traps (Newberry et al., 2017). Extraction times varied between 30-40 min for soil samples and 45-60 min for plant tissues and vapor condensates. The extracted water was sealed in glass vials with Polyseal<sup>®</sup> caps to prevent post extraction evaporation.

Isotopic composition ( $\delta^2\text{H}$ ) was analyzed using a Triple Isotopic Water Analyzer (TIWA-DLT\_EP, Los Gatos Research, ABB). Instrument calibration was performed using laboratory standards traceable to vienna standard mean ocean water (VSMOW), with analytical precision of  $\pm 0.4\text{‰}$  ( $1\sigma$ ) and a detection limit of 0.02% excess deuterium (ABB, 2021). Spectral quality and potential interferences were assessed using the integrated Spectral Contaminant Identifier within the LGR post-analysis software (LGR, 2016). Enriched and control water samples were measured within the same analytical sequence to minimize instrumental drift (ABB, 2017).

## 2.3 Statistical Analysis

**Table 5:** Summary of statistical tests applied for different studies using R (2024.12.1 Build 563).

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**Study A: Investigating soil water dynamics to improve agriculture: Namibian land-use systems under drought**

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Shapiro Wilk test indicated non-normality. Consequently, Kruskal Wallis test was applied to assess group differences among conservation agriculture (CA), traditional agriculture (TA) and woodland (W). Effect sizes were computed using Cohen's d to quantify the magnitude of differences among land-use systems and in addition percentage changes (CA vs TA; W) were assessed.

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**Study B: Soil water dynamics along the Kalahari dune transects in northern Namibia**

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Data were tested for normality using the Shapiro Wilk test and for homogeneity of variances using Levene's test. Depending upon the data distribution results, one-way ANOVA and Kruskal Wallis test was applied to assess differences in infiltration and evaporation respectively among dune positions (Dune Crest, Slope, Interdune). A linear mixed-effects model was applied to evaluate difference among soil water content at different soil depths, where, topographic position and depth level was considered as fixed variables and replication as a random variable. Effect sizes were computed using Cohen's d to quantify the magnitude of differences and percentage changes were calculated.

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**Study C: Soil water dynamics and yield responses of cowpea under conservation and traditional agriculture in northern Namibia**

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Data normality was tested using the Shapiro Wilk test and homogeneity of variances using Levene's test. Mann Whitney U test was applied to assess grain yield differences between CA and TA management. Kruskal Wallis test was applied to assess grain yield differences among inoculated, non-inoculated and nitrogen fertilized treatments under CA and TA. Pairwise post hoc analysis was done using Dunn's test. Percentage change in grain yield among treatments was calculated.

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**Study D: Cowpea growth response to mulching and inoculation modifying soil water dynamics under simulated drought**

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Linear mixed-effects model (LME) was applied to evaluate differences among treatments (Schielzeth et al., 2020), where, soil water levels, planting treatments and mulch categories were considered as fixed variables and replicates as a random factor to account for spatial variation. For phenological evaluations, the model in addition included day as a fixed variable. At distinct developmental stages ANOVA was applied to evaluate differences at planting and at treatment levels. Model assumptions were confirmed by visual inspection of the model residual (variance homogeneity) and q-q plots (normality). Tukey's HSD test was employed for post-hoc pairwise comparisons among mulching treatments.

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**Study E: Water vapor from deep soil reservoirs as a viable water source for plants in sandy soils**

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Labeled water vapor contributions were estimated using a Bayesian mixing model (MixSIAR two-end framework) with  $\delta^2\text{H}$  signatures of reservoir (512.08‰) and control water (-53.38‰). Posterior distributions and 95% credible intervals were generated. Pairwise posterior probabilities assessed overlap among treatments. One-sided Wilcoxon Mann Whitney test was applied to compare treatments and control. Treatment effects were further assessed using Kruskal Wallis analysis.

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### 3 Key Findings

**Table 6:** Overview of objectives and key findings of the studies conducted for this dissertation.

Objectives	Key Findings
<b>Study A: Investigating soil water dynamics to improve agriculture: Namibian land-use systems under drought</b>	
<ul style="list-style-type: none"> <li>To investigate the effects of land use systems, Conservation Agriculture (CA), Traditional Agriculture (TA) and Woodland (W) on soil water dynamics during crop growing period</li> <li>To assess the extent of conservation agriculture to enhance water retention and regulation under drought stress</li> </ul>	<ul style="list-style-type: none"> <li>CA increased topsoil moisture by 63.7% compared to TA → improved near surface water retention under drought conditions</li> <li>Infiltration was 62.7% lower in CA relative to TA → reduced infiltration is beneficial given the extremely high infiltration rates in sandy soils</li> <li>Despite higher soil moisture in CA → Evapotranspiration rates did not differ significantly between CA and TA → surface evaporation remained the dominant water loss pathway</li> <li>The results → CA improved soil water retention but do not necessarily translate into higher crop water use efficiency</li> </ul>
<b>Study B: Soil water dynamics along the Kalahari dune transects in northern Namibia</b>	
<ul style="list-style-type: none"> <li>To investigate how soil water dynamics, differ across the three principal topographic positions representative of the dune system (dune crest, slope, interdune)</li> <li>To evaluate the extent to which the differences in soil water dynamics across dune topography determine interdune being the key hydrological accumulation zone under prevailing semi-arid conditions</li> </ul>	<ul style="list-style-type: none"> <li>Evaporation, infiltration and soil water content showed statistically no significant differences among dune crest, slope and interdune positions</li> <li>Large effect sizes (Cohen's d) may suggest meaningful contrasts</li> <li>Infiltration although statistically insignificant, was ~25-30% (d = 0.80-0.96) lower in interdunes compared to dune crest and slope → reduced infiltration is beneficial given the extremely high infiltration rates in sandy soils</li> <li>Soil water content although statistically insignificant (at 5cm depth) was ~40% higher in interdune than in dune crest and slope → topsoil retains moisture in interdune depressions</li> <li>Interdunes may emerge as the hydrologically responsive unit of the dune transect despite the overall homogeneity of the sandy substrate</li> </ul>
<b>Study C: Soil water dynamics and yield responses of cowpea under conservation and traditional agriculture in northern Namibia</b>	
<ul style="list-style-type: none"> <li>To quantify the influence of CA and TA management practices on soil water dynamics</li> </ul>	<ul style="list-style-type: none"> <li>Soil water dynamics related effects cannot be evaluated due to unplanned irrigation and unreliable mulch conditions.</li> </ul>

- To assess the effect of mulching, in combination with *Bradyrhizobium* inoculation to improve crop yield
- Grain weight was significantly higher in CA compared to TA. Within CA, inoculated treatments had ~28.4% significantly higher grain weight than non-inoculated treatments → localized benefits of minimum soil disturbance and effects of inoculation

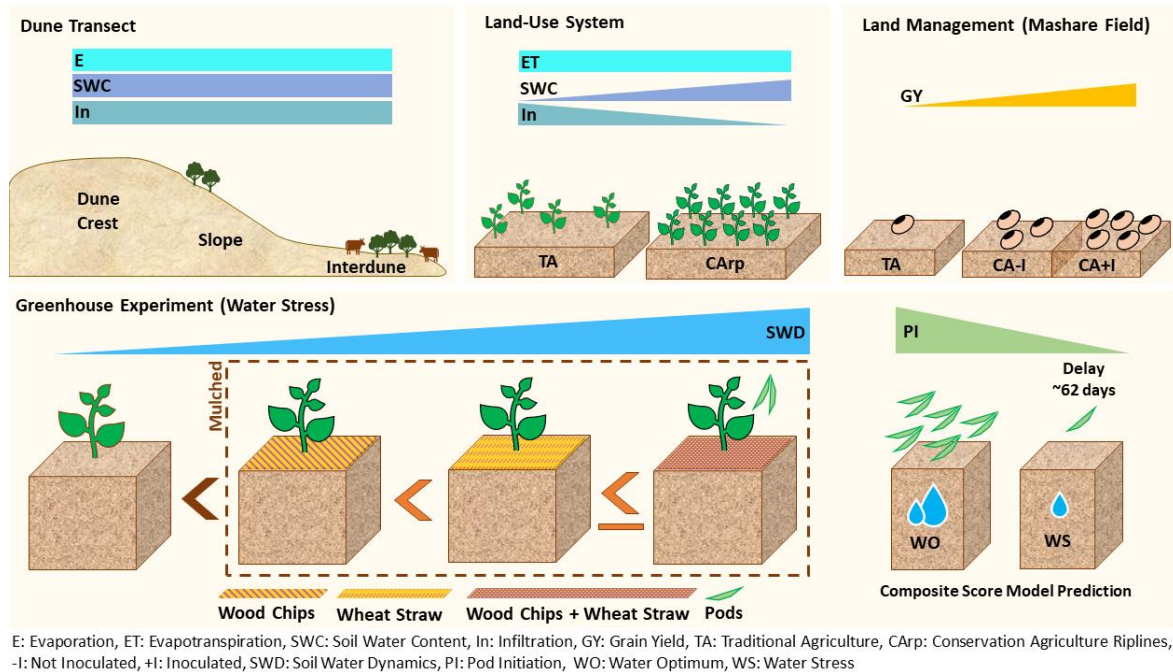
#### **Study D: Cowpea growth response to mulching and inoculation modifying soil water dynamics under simulated drought**

- To determine how different mulching materials and rhizobial inoculation influence soil water dynamics in sandy soils under drought
- To evaluate whether these interventions translate into improved developmental performance in greenhouse-grown cowpea under water stress
- Water stress reduced overall growth and delayed pod initiation by > 62 days → strong physiological limitation under drought
- Combined mulch of wood chips and wheat straw (WC+WS) improved soil water dynamics → reduced total water input by 14.9%, increased WUE by 233.3%, transpiration by 262.9%, leaflet number by 55%, stem height by 11.7%, root biomass by 68.3%, shoot biomass by 45.8% and HI from 0 to 1.6 under water stress
- Inoculation reduced root/shoot ratios by 80% → improved plant physiological efficiency
- The results → mulching particularly the combination of WC+WS → offers a sustainable, locally adaptable strategy to improve cowpea drought resilience in semi-arid sandy soils

#### **Study E: Water vapor from deep soil reservoirs as a viable water source for plants in sandy soils**

- To investigate whether plants take up water vapor from the hydraulically decoupled deep soil water reservoir
- To assess if the utilization of water vapor has a physiological relevance to the plant survival under drought conditions
- To investigate if this process can be enhanced by an agronomic management strategy, specifically, the application of mulch
- Deuterium enrichment confirmed → *Vigna radiata* saplings took up water vapor from a hydraulically separated deep water source → verifying vapor uptake under extreme drought
- Plants with access to the water vapor source survived ~ 2.7 days longer than those without → physiological relevance of vapor uptake in sustaining plant's basic metabolic processes
- Mulching enhanced vapor availability by 38.2%, extended plant survival by ~ 4.5 days compared to unmulched treatments
- Vapor flux was small (0.14 ml day<sup>-1</sup>) → were sufficient to delay wilting → even minimal vapor contributions can support plants at early developmental stages during severe drought
- Findings → agronomic practice of mulching → enhance water availability and efficiency of vapor utilization

### 3.1 Soil Water Dynamics across Land-Use and Land Management Under Drought



**Figure 11:** Summary of key findings across the dune transect, land-use system, land management (mashare field) and greenhouse experiment studies.

#### *Soil water dynamics across land-use systems*

Farmlands practicing conservation agriculture exhibited increased soil water content (63.7%, topsoil 0-10 cm) and decreased infiltration rates (62.7%) in riplines compared to farmlands under traditional agriculture, whereas, evapotranspiration rates remained comparable (Figure 11). In addition, evapotranspiration components investigated under conservation agriculture delineated that evaporation was the dominant pathway for water loss. Inclusively, the results demonstrated that conservation agriculture primarily enhanced the temporal persistence of near surface soil moisture than altering total evaporative fluxes, thereby shifting soil water dynamics toward improved water retention and consequent enhancement of plant available water under drought conditions. The investigated capacity of conservation agriculture to conserve water could establish it as an effective approach that supports the sustenance of agricultural productivity in semi-arid northern Namibia (Study A).

Improved soil water dynamics as observed in study-A could be attributed to the combined long-term effects of minimum soil disturbance (reduced tillage), retention of straw residues acting as partial soil cover and consistent crop rotation practiced by smallholder farmers at our selected sites. The recorded improvements may suggest a potential legacy effect of implemented

conservation agriculture (Cordeau, 2022; Grahmann et al., 2022). The documented relatively lower infiltration rates and higher soil water content near surface within riplines in conservation agriculture may enhance plant water availability in the rooting zone (Liu et al., 2023). It is important to note that sandy soils predominantly have extremely high infiltration and the recorded reduction, though notable still remained high  $\sim 900 \text{ mm h}^{-1}$  (Liu et al., 2019), and continue to limit plant water availability. Furthermore, the retention of crop residues potentially provided a surface barrier to evaporation (Hao et al., 2023; Steenwerth & Belina, 2008; Villarreal et al., 2021), over time contributed to soil aggregation and surface stability (de Holanda et al., 2025; Fu et al., 2021), and in combination with reduced tillage practices (Blanco-Canqui & Ruis, 2018; Mantovani et al., 2024; Skaalsveen et al., 2019) reinforced higher water content in the upper layers of soil (Abdallah et al., 2021). The results align with findings of other studies who have investigated different variables of soil water dynamics under conservation agriculture practiced in semi-arid and arid regions. Thierfelder and Wall (2009) showed that conservation agriculture fields investigated in Zambia and Zimbabwe maintained higher soil moisture in the upper soil layers compared with traditional agriculture, which supported crops during the most critical early establishment and root development stages. Bekele et al. (2022) showed that the practice of reduced tillage supported higher soil moisture retention in the rooting zone that enabled higher maize yields in semi-arid Ethiopia. Kudumo et al. (2023) showed with field investigations in Namibia that reduced tillage with soil cover retained higher soil moisture in comparison to conventionally tilled soils with no soil cover. Nonxuba et al. (2025) through a medium term implemented conservation agriculture practice in South Africa showed  $\sim 25\%$  increase in soil water content due to differential residue retention introduced via crop rotations and retained crop residues. Abdallah et al. (2021) detailed the pronounced effect of long-term conservation agriculture practice that improved near surface water holding capacity. In our study, although statistically not significant we also recorded a small increase of 1.5% in water holding capacity under conservation agriculture relative to traditional agriculture. These effects could be further associated with aggregate stabilization and shift in soil's functional porosity under conservation agriculture, promoting enhanced water retention (Bescansa et al., 2006; Corsi & Muminjanov, 2019; Villarreal et al., 2021). In addition, structural interventions such as riplines, have been investigated to improve rooting conditions and modify soil pore architecture that supports better water acquisition (Cueff et al., 2021; Jayaraman & Dalal, 2022; Kassam et al., 2022; Soane et al., 2012).

In interpreting these findings, it was important to recognize that the analysis focused primarily on topsoil conditions, even though crops have developed root

systems that extend well below the upper soil layers. Topsoil typically shows the strongest and most immediate response to management practices because it is directly influenced by evaporation, soil cover effects and the initial redistribution of infiltrating water (Han & Zhou, 2013; Z. Li et al., 2020; Shokri & Salvucci, 2011). The upper soil layer plays a decisive role in shaping how moisture profiles evolve with depth, as its sequence, thickness and physical characteristics govern how water moves downward and how evaporation diminishes through the profile (Balugani et al., 2021; Deol et al., 2014; He et al., 2023). The presence of vegetation further modifies these dynamics by altering near-surface energy balance, root water uptake and influencing the direction and magnitude of water fluxes within the profile (Dai et al., 2025; Gutiérrez-Jurado et al., 2006). The deeper soil zones may respond more slowly and are buffered from short-term surface water fluxes, often displaying distinct moisture regimes governed by lower matric potentials, reduced evaporative demand and slower hydraulic redistribution (Niu et al., 2015; Wang et al., 2020). These subsurface layers are crucial for sustaining transpiration once the surface dries (Sekhri et al., 2025), particularly in sandy soils where rapid drainage limits the persistence of topsoil moisture (Kamai & Assouline, 2018). Consequently, improvements observed in the topsoil did not reflect the full vertical distribution of plant-available water. A depth-explicit assessment is therefore essential to evaluate how surface-level gains translate into moisture supply across the entire rooting profile and to better understand the implications for crop performance under semi-arid conditions.

Regardless of these improvements in near surface soil moisture, statistically insignificant evapotranspiration rates ( $\sim 0.04 - 0.06 \text{ mm h}^{-1}$ ) between conservation and traditional agriculture indicated the non-efficient utilization of available water by crops. Although our study quantified evapotranspiration under drought, similarly low rates have been documented elsewhere. Li et al. (2003) reported evapotranspiration of  $\sim 0.17 \text{ mm h}^{-1}$  for maize under high vapor pressure deficit conditions in a partially irrigated semi-arid field in northern China. Likewise, Shahrokhnia et al. (2013) observed maximum evapotranspiration rates of about  $0.42 \text{ mm h}^{-1}$  in partially irrigated maize fields in a semi-arid region of Iran. Evaporation was investigated to be the dominant water loss pathway and low mean transpiration efficiency (0.07) documented reinforced the limited biological uptake of retained moisture under drought. These results could be attributed to the extremely high temperatures, low overall soil water content, high infiltration and exposed soil (patches due to partial soil cover) recorded in our study-A. Low transpiration rates could be a consequence of early stomatal closure, a known adaptive trait of pearl millet under drought conditions (Shrestha et al., 2023), that limits transpiration losses

but may constrain crop productivity (Comas et al., 2019). Several studies report the closure or the reduced regulation of stomata under water stress conditions (Ghatak et al., 2016; Henson et al., 2006; Tewolde et al., 1993). Overall, the water losses reported in the study represented conditions during the peak dry season with no rainfall, when temperatures were high, vapor pressure deficits were potentially elevated and topsoil moisture was low. These losses therefore reflect a period of maximum evaporative demand. During cooler or wetter parts of the year, evaporation would be potentially lower due to reduced atmospheric forcing, higher cloud cover and greater soil moisture buffering. However, in sandy soils with minimal cover, the general pattern of strong surface-driven evaporation would still occur whenever similar dry and hot conditions prevail. The topsoil water content could have been preserved and subsequently used more efficiently if soil cover had been retained consistently over time. However, in the field sites, straw residues were frequently removed for fuel and fodder, resulting in insufficient and discontinuous mulch cover. Under such local practices, soil cover as mulching was not ideal, making it necessary to explore alternative mulching options that could provide more sustained surface protection. The controlled mulching study addressed this gap by evaluating different organic mulches with improved retention and effectiveness.

### *Soil water dynamics under land management practices*

Mulching markedly improved cowpea performance under drought, as shown by higher water use efficiency and better growth dynamics (Study D). These effects are consistent with the role of surface mulches in limiting soil evaporation, buffering temperature fluctuations at the surface and sustaining greater plant available water within the rooting zone (Mulumba & Lal, 2008; Prosdocimi et al., 2016; Thierfelder & Wall, 2009; Valbuena et al., 2012; Zribi et al., 2015). By creating a more stable soil microenvironment and reducing evaporative losses, mulches allowed plants to maintain physiological processes for longer under limited water supply, thereby improving water use and overall development (Cadavid et al., 1998; Díaz et al., 2022; Fér et al., 2022; Rossi et al., 2024). Relative to the no-mulch treatment (PI), the combined wheat straw and wood chip mulch (PI+WC+WS) lowered total water input by 14.9%, increased water use efficiency by 233.3%, enhanced transpiration by 262.9% and promoted growth, including 55% more leaflets, 11.7%, greater stem height and an increase in harvest index from 0 to 1.6 in one replicate. It is important to acknowledge that this study was conducted in a pot-based setup in a greenhouse and field-scale outcomes may differ due to greater environmental variability and soil heterogeneity. Nevertheless, the direction and magnitude of

the responses we observed are supported by several experimental and field studies using straw or wood chip mulches, which have reported similar improvements in soil water retention and plant growth, even though these materials have rarely been applied together as a combined mulch. Peng et al. (2015) reported that straw mulching increased average soil water content in the 0-200 cm profile by 0.7-22.5%, raised water use efficiency by 24-33% and enhanced grain yield by 13-23% compared with the control (no mulch) under dryland farming. In another study, Goel et al. (2019) reported that wheat straw mulch increased soil moisture by 42% at 10 cm depth (compared with 32% under rice straw) and by 5-16% at 20 cm under coarse-textured sandy loams, and attributed these differences to the finer micro-tubular structures in wheat straw that enhanced moisture retention, reduced downward percolation and helped maintain water in the shallow root zone. Jordán et al. (2010) found that applying wheat straw mulch at higher application rates of 10-15 Mg ha<sup>-1</sup> year<sup>-1</sup> increased field capacity up to 28.5%, saturation water up to 50.5%, raised available water content to 18% and increased the wilting point up to 30.3% under semi-arid conditions of Spain. Van Donk et al. (2011) showed that applying 2.5-10 cm wood chips mulch consistently conserved soil water compared with bare soil, moderated soil temperature, reduced weed pressure and produced modest improvements in plant growth of *Penstemon digitalis* in loamy silt soils in Nebraska. Hallman et al. (2023) showed that three years of annual hardwood oak mulch applications improved seasonal soil moisture by 25-88% in alfisols of a citrus farm in Florida.

The enhanced performance of the mixed mulch as documented in study-D likely reflects the complementary properties of the two materials. Wheat straw, with its finer structure and higher surface area, effectively reduces evaporative losses and improves near-surface moisture retention (Wang et al., 2022), while wood chips, being coarser and more persistent, moderate soil temperature and enhance aeration (Appiah et al., 2023; van Donk et al., 2012). When applied together, these contrasting physical characteristics may create a more heterogeneous and stable surface cover that suppresses evaporation, buffers the soil microclimate and prolongs the retention of plant available water more effectively than either material alone as shown with study-D. The inclusion of wood chips potentially will strengthen mulch durability under field conditions, where high temperatures, wind exposure and microbial activity typically accelerate the breakdown of fine residues (Henschke & Politycka, 2016; Klimek et al., 2020; Wang et al., 2025). Wood chips with greater structural stability may help maintain surface cover for extended periods and improve resistance to wind erosion, as illustrated by the increased stability of thick straw-aggregate layers reported by Fuchs and Hadas (2011). Such prolonged surface cover is

particularly important in semi-arid sandy systems, where the continuity and persistence of mulch strongly influence soil water conservation and plant performance under drought (Demo & Asefa Bogale, 2024; Mangani et al., 2022; Rocco et al., 2024). Moreover, in Namibia, the availability of large volumes of woody biomass generated from the management of bush encroachment offers a practical opportunity to supply the wood chip component of such mulch mixtures, providing a locally accessible and sustainable resource (Kariuki et al., 2025; Schick & Ibisch, 2021). The combined use of such woody materials with limited straw crop residues may therefore represent a feasible approach to improving soil water dynamics through surface cover, although the extent of effectiveness of these mulch types remains to be evaluated under field conditions.

Despite the strong positive effects of mulching on soil water availability and cowpea development, these benefits did not consistently translate into reproductive success under the imposed drought conditions in our greenhouse experiment (Study D). Pod formation remained highly restricted, occurring only in a single replicate of PI+WC+WS treatment. Composite score modelling further suggested delays of more than ~62 days in reaching pod initiation threshold under water stress, far beyond the period in which cowpea is typically cultivated. This indicated that, although mulching improved the physiological conditions necessary for vegetative growth, the water conserved was either insufficient in magnitude or not effectively utilized to sustain reproductive development. These findings point to the need for additional, complementary strategies that can help convert improved soil moisture conditions into yield gains under drought, motivating the subsequent evaluation of inoculation effects.

As a complementary strategy, inoculation with *Bradyrhizobia* further supported cowpea performance under conservation agriculture. In Study D, inoculated planted treatment with mixed mulch (PI+In+WC+WS) exhibited an ~80% decrease in root-to-shoot ratio compared with non-inoculated planted treatment (PI), indicating a shift in biomass allocation toward aboveground tissues under water limited conditions (Kyei-Boahen et al., 2017; Rocha et al., 2019). Inoculation in combination with mulching suggested potential synergistic effects, as inoculated planted treatments with mixed mulch (PI+In+WC+WS) and wheat straw (PI+In+WS) tended to exhibit higher shoot biomass (Nyoki & Ndakidemi, 2014; Tankari et al., 2019), however, these differences were not statistically significant and remained variable among replicates. However, these positive feedbacks in biomass allocation were not sufficient to induce pod formation under the drought conditions imposed in the greenhouse experiment, indicating that water limitation remained the dominant constraint on reproductive development.

On the contrary, under field conditions at Mashare (Study C), inoculation effects were pronounced, where inoculated cowpea achieved 28.4% higher grain yield than non-inoculated treatments under conservation agriculture. These results align with earlier work showing that rhizobial inoculation improves performance in semi-arid environments by enhancing nitrogen fixation and supporting growth under limited moisture (Adeyemi et al., 2025; Boddey et al., 2017; da Silva Júnior et al., 2018; Danso et al., 2025; Grönemeyer, 2013; Nyoki & Ndakidemi, 2014; Tankari et al., 2019). Enhanced nodulation underpins these improvements, as effective symbiotic nitrogen fixation strengthens plant nutrition and vegetative development in legumes (Martins et al., 2003; Sarkar et al., 2023a; Yanni et al., 2016). In northern Namibia, native nodulation efficiency is often low due to poor soil conditions (Grönemeyer, 2013), highlighting the relevance of climate-adapted rhizobial strains that can improve nodule formation and nitrogen-fixing capacity of legumes (Becker et al., 2024; Grönemeyer & Reinhold-Hurek, 2018; Luchen et al., 2018). This potential remains sensitive to soil moisture, as drought limits nodule function and the physiological benefits inoculation can deliver (Melo et al., 2025).

In summary, the combined effects of mulching and inoculation indicated complementary roles, but their expression depended strongly on the severity of water stress. In the greenhouse experiment, where water stress was maintained consistently and at high intensity (20% of the maximum water holding capacity), neither practice was able to overcome the limitation on reproductive development (except in one replicate of PI+WC+WS). However, under the partially irrigated field conditions at Mashare, inoculation contributed to a clear increase in grain yield. This contrast also supports that the benefits of inoculation may be more pronounced under moderate rather than extreme water limitation, a pattern that should be examined further through additional field trials, semi-controlled experiments and evaluations across different soils and stress levels.

### *Soil water dynamics across dune transect*

Beyond the management level, the dune transect analysis provided useful insights into how soil water dynamics vary naturally across the dune crest, slope and interdune positions. Evaporation, infiltration and soil water content showed statistically no significant differences among the three topographic positions (Figure 11). However, several large effect sizes (Cohen's  $d$ ) suggested tendencies toward improved soil water dynamics in interdune. Infiltration was 25-30% lower and soil water content (at 5 cm depth) was ~40% higher in interdune compared with dune crest and slope positions (Study B), suggesting that interdunes may function as localized zones of hydrological accumulation.

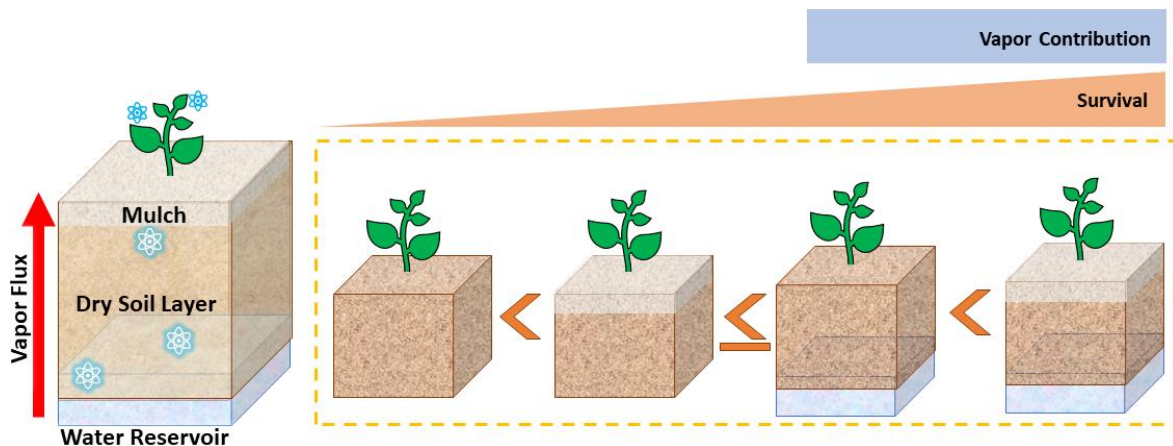
It is important to note that although infiltration was slower in the interdunes, a potential advantage given the typically rapid infiltration of sandy soils, it remained relatively high ( $\sim 1500 \text{ mm h}^{-1}$ ) and may still limit the persistence of moisture in the topsoil. These inferred tendencies are supported by findings from other dune-based soil water balance studies. Zhou et al. (2017) reported that small elevation differences can promote lateral redistribution of infiltrated water during rainfall events, enabling interdunes to retain slightly more moisture, although topsoil moisture differences between slope and interdune positions remained marginal under dry period following rainfall. Similarly, Berndtsson et al. (1996) showed that in pervious, homogeneous dune sands of northwestern China, most effective infiltration occurred at dune crests and interdunes, with water from the slopes being transported laterally downslope and accumulating in interdunes during rainfall. Rummel and Felix-Henningsen (2004) observed that near-surface soil water content was generally higher in interdunes than on dune crests and slopes in the sandy Nizzana dune field, although much of this moisture was not readily plant-available and infiltration rates were often higher on slopes than in interdunes. These tendencies align with known geomorphic and pedogenic processes in the north-eastern Kalahari (in Namibia), where dunes exhibit relatively low relief and shallow interdunes (Lancaster, 1988; White et al., 2015). Over time, reduced wind exposure in interdunes has allowed finer sediment to accumulate (Gadal et al., 2022; Thomas, 1988), while their low-lying position promoted lateral convergence of infiltrated water from surrounding dune sands (Garzanti et al., 2022a; Stone et al., 2022). These conditions gradually modified micro-topography, enabling marginally higher short-term moisture retention in interdune (Li & Ravi, 2018; Zhou et al., 2017) and supported vegetation establishment (Pröpper et al., 2010).

Over time, through organic matter inputs and partial shading, vegetation further reduced evaporative losses and subtly enhanced near-surface water holding capacity (Bhattachan et al., 2014; Porporato et al., 2003; Wiggs et al., 1995). Vegetation patterns in the Kalahari reflect these moisture contrasts, where, dune crests typically support sparse grasses and small shrubs, whereas interdunes sustain denser woody shrubs and seasonal grasses (Burke, 2002; Pröpper et al., 2010). Interdunes also have been reported to intermittently retain shallow ponding or elevated soil moisture after intense rainfall events, creating localized zones of increased fertility (Burrough et al., 2015) that enhance germination and vegetation establishment (Jolivet et al., 2022).

The measured soil water dynamics represent conditions during the peak summer period, characterized by high temperatures and the absence of rainfall, and are therefore limited in their temporal scope. Under more variable climatic

conditions, including seasonal shifts in precipitation and atmospheric demand, soil water dynamics may differ, indicating the need for further investigation across a broader range of environmental settings.

### 3.2 Water Vapor Uptake and Plant Survival Under Severe Drought



**Figure 12:** Summary of key findings for water vapor uptake and plant survival under extreme drought. The illustration on left shows vapor flux from a subsurface water reservoir through a dry soil layer toward the root zone. The series on the right depicts the comparative survival potential of plants across treatments.

At soil-plant-vapor interface, the column experiment (Study E) provided clear evidence that *Vigna radiata* saplings can access and utilize water vapor originating from a deep, hydraulically isolated reservoir. Bayesian posterior probability analysis revealed that mulched treatment (PI+M) had a 38.2% probability of having higher water vapor contribution to *Vigna radiata* saplings than unmulched treatment (PI). Under mulched conditions saplings survived significantly longer ( $\sim 2.7 - 4.5$  days) than those without (Figure 12). Although the measured vapor flux was small ( $\sim 0.14 \text{ ml day}^{-1}$ ), it was physiologically meaningful. A Fick's law estimates of  $\sim 0.29 \text{ ml day}^{-1}$  confirmed that the observed uptake was consistent with vapor diffusion through the 55 cm sand column. These results demonstrated that even minimal water vapor flux can substantially delay wilting, highlighting the supplemental role of water vapor pathways in sustaining plant function when liquid water is unavailable.

The outcomes align with Mahdavi et al. (2020), who calculated vapor transport to be only about  $\sim 1\%$  of the total soil moisture flux and Zheng et al. (2020) who showed that such small vapor fluxes are nonetheless sufficient to support plant functioning in extreme drought. In coarse-textured sandy soils such as those of the Kavango, characterized by low matric potential and

discontinuous hydraulic connectivity, water vapor diffusion could become a dominant transport mechanism once the capillary rise of liquid water breaks (Deol et al., 2014; Wang et al., 2020). This helps explain how sparse vegetation persists during prolonged dry periods (Siyambango et al., 2022), even when soils appear to be completely dry.

Several mechanisms could account for the uptake of water vapor observed in this study. While foliar water uptake is known to occur in some species (Berry et al., 2019), it is unlikely here due to the constant flushing of headspace air, which would have reduced vapor concentrations available for leaf absorption. Another mechanism could be the root-mediated uptake of water vapor. While roots can sense gradients in water vapor concentration (Lind et al., 2021), there currently is no conclusive evidence that they can directly absorb water vapor. The consistent deuterium enrichment across both mulched and unmulched treatments instead supports a potential soil-mediated pathway, where water vapor first condenses on soil particles before being absorbed by roots. This indirect mechanism is widely recognized (Bhattacharya, 2021; Chen et al., 2020; Steudle, 2000) and has been demonstrated experimentally in controlled systems (Assouline et al., 2013; Deol et al., 2014). Condensation is enhanced by temperature gradients, diurnal fluctuations and the presence of mulch, all of which promote localized microenvironments with improved water availability and prolong residence time of water vapor in the soil matrix (Demo & Bogale, 2024; Ramos et al., 2024). In our experiment, mulching amplified the probability of water vapor uptake by reducing surface evaporation, increasing water vapor residence near the surface and improving the likelihood of condensation at the 0-5 cm depth layer.

The physiological outcomes of these processes were clear, despite the lack of free liquid water, biomass loss did not significantly differ among treatments (Study E), indicating that water vapor uptake acted as a supplemental water source, allowing plants to maintain basic metabolic functions without promoting growth (Kool et al., 2021). Together, these results reveal that water vapor represents a previously underappreciated component of the soil-plant-water continuum, particularly in semi-arid sandy soils where liquid water is ephemeral. Water vapor diffusion offers a mechanism by which plants can access subsurface moisture long after rainfall has evaporated or drained, while surface mulches strengthen this pathway by modifying temperature and humidity at the soil-atmosphere interface. Integrating water vapor processes into the broader conceptual framework of soil water dynamics, alongside infiltration, retention and evaporation, provides a more complete understanding of plant persistence under severe drought and highlights new directions for both research and management in dryland agriculture.

## 4 Conclusion and Outlook

### 4.1 Conclusion

This dissertation examined the soil water dynamics in the sandy soils of northern Namibia, addressing how land-use, land management including surface modifications and vapor-phase processes collectively influence water availability and plant survival under drought. By integrating field, greenhouse and column-scale experiments, the study established a coherent framework linking hydrological buffering at the soil surface with physiological resilience in plants.

At the land-use scale (Study A), conservation agriculture primarily enhanced the temporal persistence of near-surface soil moisture rather than altering total evaporative losses. Riplines under conservation agriculture had higher soil water content in the upper soil layers and showed reduced infiltration relative to traditional agriculture. Despite these positive findings, infiltration rates still remained high and evapotranspiration was dominated by evaporation, therefore limiting plant available water. These findings indicated that in the Kavango region of northern Namibia, implemented conservation agriculture by small-holder farmers was limited in its ability to convert improved topsoil moisture into higher transpiration efficiency and productivity under peak dry season conditions. The strong focus on topsoil further highlighted that improvements in the upper layers do not necessarily reflect the full vertical distribution of plant available water, underscoring the need for depth-explicit assessments when evaluating crop performance under water-limited conditions.

The greenhouse experiment (Study D) demonstrated that surface cover can substantially enhance plant water use and vegetative development of cowpea under drought. The mixed wheat straw and wood chip mulch markedly increased water use efficiency, transpiration and harvest index relative to unmulched treatments, which confirmed the potential of straw and woody mulches to improve topsoil water retention and consequent plant performance under semi-arid conditions. Mechanistically, the complementary properties of fine, evaporation suppressing wheat straw and coarse, structurally stable wood chips offer a promising combination for sandy systems where rapid residue breakdown and wind exposure constrain mulch persistence. However, even with these clear biophysical gains, pod formation remained strongly suppressed in the greenhouse, indicating that under extreme water limitation improved vegetative conditions do not automatically translate into reproductive success.

Moreover, inoculation with *Bradyrhizobia* emerged as a complementary strategy that can enhance the benefits of improved topsoil moisture, particularly under water stress. In the greenhouse experiment (Study D), inoculation

reduced root-to-shoot ratio and showed a tendency toward biomass allocation in shoots, highlighting its synergistic effects with mulching, but did not overcome the reproductive bottleneck under water stress. In contrast, field trials at Mashare (Study C) revealed a clear yield benefit, with inoculated cowpea achieving substantially higher grain production under conservation agriculture. The positive effects of inoculation on nodulation and nitrogen fixation were fully expressed under field conditions with partial irrigation. Overall, the combined roles of mulching and inoculation are complementary but only partially buffering when drought intensity is very high.

The dune transect analysis (Study B) showed that soil water dynamics are only weakly structured by topography, with statistically no significant differences in evaporation, infiltration or soil water content among dune crest, slope and interdune positions. Nevertheless, effect-size patterns and supporting literature pointed to a tendency for interdunes to exhibit slightly lower infiltration and higher near-surface moisture, consistent with their role as shallow hydrological accumulation zones. These subtle differences can be explained by small elevation gradients, finer sediment accumulation, lateral redistribution of infiltrated water and the overtime development of denser vegetation and higher organic matter in interdunes. Thus, even within a seemingly homogeneous sandy substrate, modest geomorphic contrasts create hydrologically responsive zones that may serve as micro-environments for plant establishment and persistence.

Finally, the water vapor column experiment (Study E) extended the conceptual framework beyond liquid water acquisition and utilization, demonstrating that plants can draw on water vapor as a supplemental water source under extreme drought. *Vigna radiata* saplings accessed water vapor originating from a deep hydraulically isolated reservoir, and mulching increased the likelihood and functional impact of this water vapor uptake. Despite the very small measured water vapor flux, water vapor contribution was sufficient to delay wilting and extend survival, acting as a supplemental water resource rather than supporting additional growth. These results, together with published estimates that water vapor constitutes only a minor fraction of total soil moisture flux, showed that small water vapor transfers can nevertheless be physiologically significant when liquid water is absent, particularly in sandy soils where the formation of a dry soil layer and the disruption of hydraulic connectivity is prevalent.

Overall, this work demonstrated that soil water conservation and plant survival in semi-arid sandy soils depended on an interplay and the extent of the implementation of conservation management practices. Integrating this gained knowledge into soil-plant-water frameworks could contribute in designing

management strategies toward sustaining crops under the pressure of drought in semi-arid northern Namibia.

## 4.2 Future Research Perspectives

This dissertation represents one of the few integrative research efforts to examine soil water dynamics across field and experimental scales under the semi-arid conditions of northern Namibia. While the results advance mechanistic and applied understanding, they also highlight several important directions for future research.

First, although conservation agriculture improved near-surface soil moisture, its effects did not translate into higher crop water use under drought. Future studies should incorporate depth-explicit monitoring to determine how surface-level improvements propagate into deeper rooting zones across seasons. Long-term field trials combining residue retention gradients, reduced tillage intensities and ripline configurations could clarify how structural and agronomic refinements influence rooting depth, hydraulic redistribution and seasonal plant water supply. Testing these refinements across different soil textures in Namibia would help identify context-specific thresholds at which conservation practices meaningfully enhance plant performance.

Second, the greenhouse experiment with sustained mulching demonstrated substantial gains in water use efficiency and vegetative development, especially with mixed wheat straw and wood chip mulch. Yet reproductive development remained limited under drought. Future work should evaluate mixed mulch systems under field conditions, including the effects of wind, decomposition rates, microbial activity and temperature buffering. Given the availability of large volumes of woody biomass from bush encroachment, research should quantify how locally sourced wood chips influence soil structure, organic matter inputs, nutrient cycling and mulch persistence over multiple seasons. Multi-year studies are needed to assess whether mixed mulches can sustainably improve soil water dynamics and crop productivity under varying climatic conditions.

Third, inoculation effects were strongly context-dependent. In the greenhouse, inoculation improved vegetative biomass allocation but did not induce pod formation, whereas in Mashare field plots it significantly increased grain yield. This underscores the need to test combined mulching-inoculation systems under a wider range of moisture regimes, soil types and environmental conditions. Detailed bio-physiological measurements such as stomatal conductance, photosynthesis, nitrogen assimilation and root-microbe inter-

actions would help identify the conditions under which inoculation most effectively enhances plant performance in sandy semi-arid systems.

Fourth, the dune transect study revealed subtle but meaningful tendencies toward improved moisture conditions in interdunes, yet the broader hydrological functioning of the dune landscape remains insufficiently quantified. Long-term monitoring of infiltration, near-surface water content, microclimate and vegetation response across dune-interdune gradients is crucial to understand how episodic rainfall, lateral flow of infiltrated water, percolation and vegetation feedbacks shape natural moisture sinks. Spatial modelling and remote-sensing approaches could further clarify the role of low-relief dune systems in shaping soil water dynamics.

Finally, the soil-plant-vapor experiment highlighted a rarely quantified but functionally important mechanism of plant survival under extreme drought. While the controlled column experiments isolated water vapor diffusion, the field relevance of water vapor derived hydration in inland semi-arid sandy systems remains largely unknown. Future studies should therefore deploy isotope tracing, high-resolution humidity and temperature profiling and diurnal monitoring to capture water vapor diffusion, condensation and plant uptake in natural settings. Incorporating dew formation, mulch-induced boundary layer effects and day-night thermal gradients would help determine how water vapor dynamics operate in field sandy soil conditions. Modelling approaches that integrate water vapor diffusion with surface microclimate variability, residue cover and plant physiology could clarify the climatic conditions under which water vapor uptake contributes meaningfully to plant water supply.

Together, these research directions underline the importance of multi-scale, process-based investigations that link land management practices, biological inputs, geomorphic context and water vapor movement. Advancing this work will support the development of resilient agricultural strategies capable of sustaining productivity in the sandy semi-arid environments of northern Namibia and similar dryland systems worldwide.

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# Manuscripts





## **Study A: Investigating soil water dynamics to improve agriculture: Namibian land-use systems under drought**

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## **Origin**

This case study originates from field research conducted as part of a doctoral project at the Institute of Soil Science, University of Hamburg, under the SUSTAIN project funded by the Federal Ministry of Research, Technology and Space Germany. The study was carried out in the Kavango region of Northern Namibia, where the ongoing challenges of drought and declining soil productivity have raised interest in sustainable land-use strategies. Drawing from long-term implementation of Conservation Agriculture practices by local farmers, supported through extension programs and international partnerships, this study aimed to generate field-based, empirical evidence to investigate soil water dynamics under different land-use systems.

## **Summary**

Subsistence farmers in Namibia's semi-arid regions face acute water constraints that undermine agricultural productivity. Regional land-use systems critically influence soil water dynamics under drought stress. This study offers rare in situ evidence on the performance of these systems during extreme water scarcity, underscoring water conservation's centrality to the sustainability and resilience of dryland agriculture.

## **A Abstract**

Water scarcity presents a critical limitation to sustainable agricultural productivity in the semi-arid region of Northern Namibia, where sandy soils and irregular precipitation challenge subsistence farming systems. Regional land-use practices significantly alter soil water dynamics under drought conditions. However, field-based quantification of the key parameters that define these dynamics remains limited. This study investigates the impacts of land-use systems, notably, Conservation Agriculture (CA), Traditional Agriculture (TA) and Woodlands (W) on soil water dynamics through in situ assessment of evapotranspiration, soil water content and infiltration during the 2024 pearl millet growing season. Using a closed-chamber method, time-domain reflectometry (TDR) sensor and double ring infiltrometer under consistent weather conditions, we demonstrate that CA significantly enhanced soil water balance. Particularly within riplines, CA reduced infiltration and increased soil water content with very large effect sizes (Cohen's  $d = -2.45$  and  $1.30$ ,

respectively), compared to TA. Evapotranspiration did not differ significantly between CA and TA, as, CA exhibited evaporation dominated water losses with consistently low transpiration-to-evapotranspiration (T/ET) ratios (median = 0.07) across all investigated farmlands, indicating limited crop water uptake. These findings provide empirical evidence of CA's role in enhancing soil water conservation in dryland systems, reinforcing the imperative for water conserving management strategies under intensifying climatic constraints.

### **Learning Outcomes**

- Interpret how different land-use systems affect water movement and retention in sandy soils under drought conditions.
- Evaluate the benefits of Conservation Agriculture for sustainable soil water management for dryland farming.
- Critically evaluate the role of land-use decisions in shaping sustainable and climate resilient agriculture.

### **Which Sustainable Development Goals (SDGs) Does the Case Support?**

Goal 2: Zero Hunger – Supports improved agricultural productivity and drought resilience.

Goal 13: Climate Action – Encourages adaptive farming practices in water-scarce environments.

Goal 15: Life on Land – Promotes sustainable soil and water management.

## **A1 Background and Context**

In semi-arid regions of Northern Namibia, agricultural productivity is increasingly threatened by erratic precipitation, elevated evaporative demand and inherently low soil fertility (Assefa et al., 2018; Ngoma et al., 2021; Shiimi & Uchezuba, 2025). Under these agroecological conditions, particularly smallholder farmers cultivating sandy soils face critical water-related constraints (Kudumo et al., 2023), including rapid top soil moisture loss, low water use efficiency and prolonged drought periods (Abdallah et al., 2021; Irkiso et al., 2025; Taapopi et al., 2018). These factors collectively hinder the attainment of self-sufficiency by smallholder farmers (Corsi & Muminjanov, 2019; Shiimi &

Uchezuba, 2025). Addressing these challenges requires an understanding of soil water dynamics, not merely in terms of soil water retention capacity, but also the ability of plants to utilize the available water effectively (Amami et al., 2021; Dexter, 1988; Głąb & Kulig, 2008; Ramezani Etedali et al., 2025). Therefore, improved insight into water flow and retention processes is critical for designing sustainable and climate-resilient agricultural improvements (Irkiso et al., 2025).

To address these vulnerabilities, Conservation Agriculture (CA), a land-use system built on the principles of minimum soil disturbance, permanent soil cover, crop diversification and intercropping has been introduced as a climate-resilient alternative to Traditional Agriculture (TA), which is typically characterized by repeated tillage, monocropping and continuous soil exposure (Corsi & Muminjanov, 2019; Dumanski, 2006; Siyambango et al., 2022). However, the influence of these land-use systems on soil water dynamics for smallholder farmlands under water limited conditions remain insufficiently investigated, even though the potential of agricultural improvements for dryland systems is well recognized (Irkiso et al., 2025).

Conservation agriculture has demonstrated agronomic benefits in numerous dryland systems (Dumanski, 2006), where, profoundly tillage and mulching practices have played a pivotal role in regulating soil hydraulic properties, including infiltration rate, water retention and redistribution (Amami et al., 2021; Dexter, 1988; Głąb & Kulig, 2008). These parameters are especially critical in water-limited systems, where soil moisture availability governs plant development and mediates drought resilience (Ngoma et al., 2021; Selvakumar & Sivakumar, 2021). In addition, conservation agriculture, in contrast to traditional agriculture, offers a less energy-intensive alternative that enhances soil structure, preserves organic matter and reduces evaporative losses (Dumanski, 2006; Kassam et al., 2022; Selvakumar & Sivakumar, 2021). Conservation agriculture may mitigate these effects by improving soil water balance and buffering climatic extremes (Kudumo et al., 2023). However, the context-specific impacts of no-tillage remain insufficiently researched (Cueff et al., 2021; Irkiso et al., 2025) and therefore, particularly under drought conditions, the hydrological outcomes may become more pronounced and unpredictable.

This study aims to quantify the effects of different land-use systems, on soil water dynamics in the Kavango region of Northern Namibia. Through field-based assessment of evapotranspiration, top soil moisture, infiltration and associated soil properties, we evaluated three land-use systems: Conservation Agriculture, Traditional Agriculture and remaining Woodlands (W). The investigation addressed two key questions, I) do land-use systems significantly influence soil water dynamics, particularly in terms of top soil moisture retention, infiltration

and surface water loss during crop growing period? and II) to what extent does conservation agriculture enhance water retention and regulation under drought stress? This work is grounded in recent evidence demonstrating improved soil moisture and crop yields under conservation agriculture, particularly where mulching and crop rotation are applied, yet it advances the discourse by providing mechanistic insights for soil water dynamics based on in situ measurements under real drought conditions.

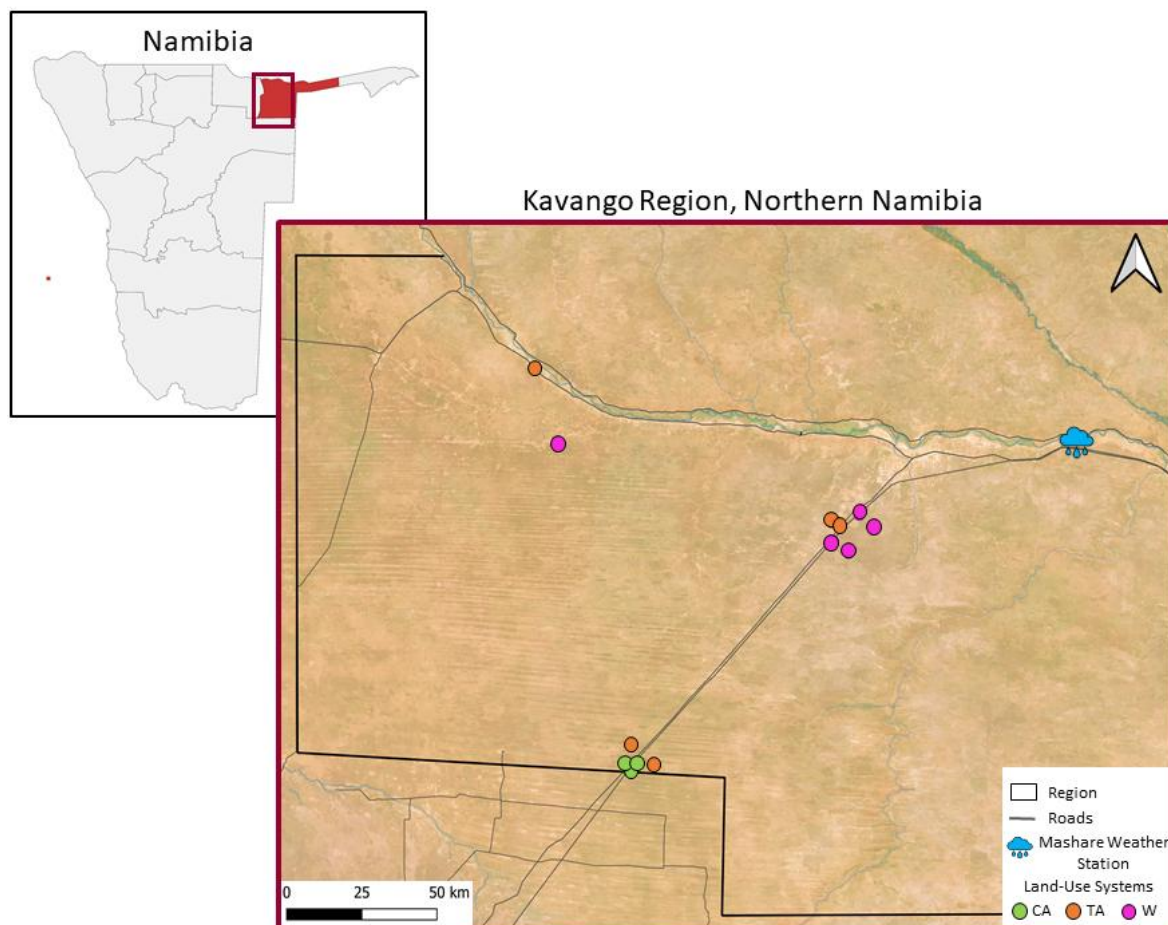
## A2 Methods

### A2.1 Study Site

The study was conducted in the Kavango region of Northern Namibia, a semi-arid landscape characterized by sandy soils, sparse vegetation cover and high interannual variability in rainfall (Gröngröft et al., 2013a; Shiimi & Uchwezuba, 2025). The region experiences a unimodal rainfall regime, with annual precipitation ranging between 450–550 mm, with the majority falling between November and March (Awala et al., 2019). Mean annual temperature range from 20–24°C, with frequent episodes of extreme daytime heat during summer months (Iortyom et al., 2022). The soils are predominantly classified as Arenosols, with high sand content, low organic matter, weak structural stability and limited water retention capacity (ANT, 2022; Gröngröft et al., 2013b).

Field investigations were carried out across different land-use systems represented by smallholder farms that have been consistently managed under traditional and conservation agriculture, alongside near-natural reference sites situated within community forests (woodlands) (Figure A1). Traditional agriculture in the Kavango region is a rainfed subsistence farming system (Mendelsohn, 2009). The investigated traditional agricultural fields were characterized by conventional tillage using ploughs or harrows, no soil cover and monocropping systems (Siyambango et al., 2022; Uchezuba & Mbai, 2020). In contrast, conservation agricultural fields had been under reduced tillage for over six consecutive years, incorporating riplines (planting furrows), partial soil cover with mulch and crop rotations (Dumanski, 2006; FAO, 2014). The investigated fields followed a crop rotation system alternating between cowpea (a legume) and pearl millet (UNDP, 2010). All farmlands cultivated pearl millet (*Pennisetum glaucum*, locally known as Mahangu) during 2024 growing season (Figure A2). Woodland sites, considered as the reference of near-natural conditions, represented minimally disturbed savanna systems, dominated by

shrubs, grasses and woody vegetation, with limited grazing pressure. A brief overview of baseline soil physical and chemical properties for all land-use types is provided in Table A1.



**Figure A1:** Geographic region of Kavango, Northern Namibia (MapChart, 2025). The map details the spatial layout of clusters of Traditional Agriculture (TA), Conservation Agriculture (CA) and Woodland (W) sites (QGIS 3.28.3).

**Table A1:** Soil properties across Conservation Agriculture (CA), Traditional Agriculture (TA) and Woodland (W) sites at 0-10 cm depth.

Soil Properties	CA	TA	W
BD (g/cm <sup>3</sup> )	1.57 ± 0.02	1.58 ± 0.05	1.53 ± 0.03
WHC%	28.70 ± 1.06	28.26 ± 1.36	31.16 ± 1.00
SOC%	0.19 ± 0.02	0.19 ± 0.06	0.50 ± 0.05
C/N	12.54 ± 1.03	12.56 ± 3.67	17.15 ± 2.18
pH (H <sub>2</sub> O)	6.55 ± 0.17	6.57 ± 0.35	5.71 ± 0.24
Sand%	91.73 ± 0.64	93.66 ± 3.09	96.67 ± 0.77

\*Here, BD: bulk density, WHC: water holding capacity, SOC: soil organic carbon and C/N: soil organic carbon by total nitrogen ratio.

### Conservation Agriculture



### Traditional Agriculture



### Woodland



**Figure A2:** Representative field conditions of the three land-use systems investigated, Conservation Agriculture, Traditional Agriculture and Woodland sites (Pictures from 2024 field work by Sekhri, S.).

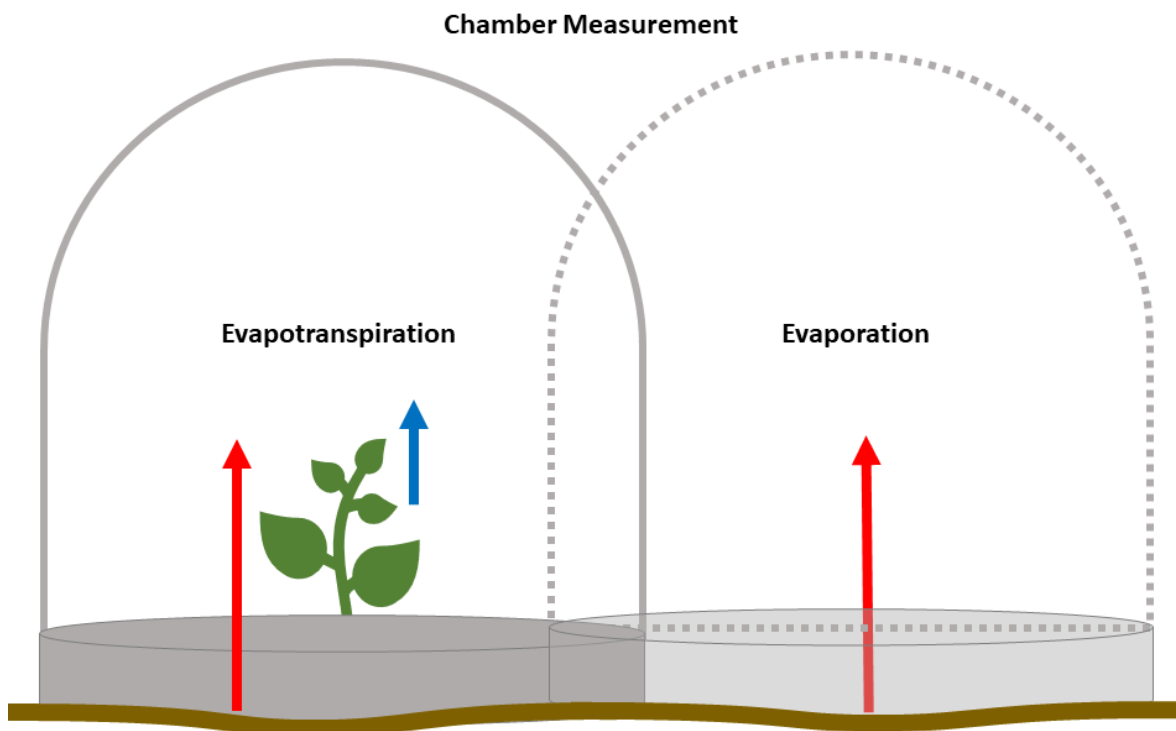
## A2.2 Experimental Design

The study was planned across five representative sites for each land-use system (CA, TA, W, Figure 1). For conservation agriculture, four sites are included for analysis, as one of the sites was ploughed before the measurement period. Field-scale assessments were conducted during the growing period, between March and April 2024. For this study, the soil water dynamics was characterized by three key parameters: **Evapotranspiration**, **Soil Water Content** and **Infiltration**.

**Chamber-based Evapotranspiration (ET)** measurements were conducted using a UV-transmissive plexiglass hemispherical chamber (56cm height, 49cm diameter), placed over cylindrical PVC collars (20cm height, 49cm diameter, 5mm wall thickness), each enclosing a single pearl millet plant (Figure A3). The soil was compacted around the collars to minimize lateral vapor exchange. Visually, plants were selected that reflected the average of the specie per site (Stannard, 1988). The chamber housed sensors for air temperature ( $^{\circ}\text{C}$ ), relative humidity (%), air pressure (hPa) and solar radiation ( $\text{W}/\text{m}^2$ ), with an adjustable fan for internal air circulation (Reicosky & Peters, 1977). All sensors were connected to an Arduino microcontroller with a datalogging shield, real-time clock and SD card, which recorded data every 3 seconds (Macagga et al., 2024). At each site, three measurements were conducted (5 minutes per replication), repeated over three separate days under similar weather conditions. In addition, **soil water content** was measured using a time domain reflectometry (TDR) sensor, at three randomly selected points around chamber collar, during each chamber session. **Infiltration** was assessed using a double ring infiltrometer (Gregory et al., 2005) with a custom-build pressure sensor. For each site, five replications were conducted to account for within site variability.

## A2.3 Data Analysis

Evapotranspiration rates ( $\text{mm}/\text{h}$ ) were derived from chamber-based measurements using Magnus equations (Bonhold, 2021; Junzeng et al., 2012; Kudumo et al., 2023). Statistical analysis was performed using R version 2024.12.1 Build 563. Shapiro Wilk test indicated non-normal distribution of data. Consequently, Kruskal Wallis test was applied to assess differences among treatment groups (CA, TA and W). Effect sizes were computed using Cohen's  $d$  to quantify the magnitude of differences among land-use systems and in addition percentage changes (CA vs TA; W) were assessed.



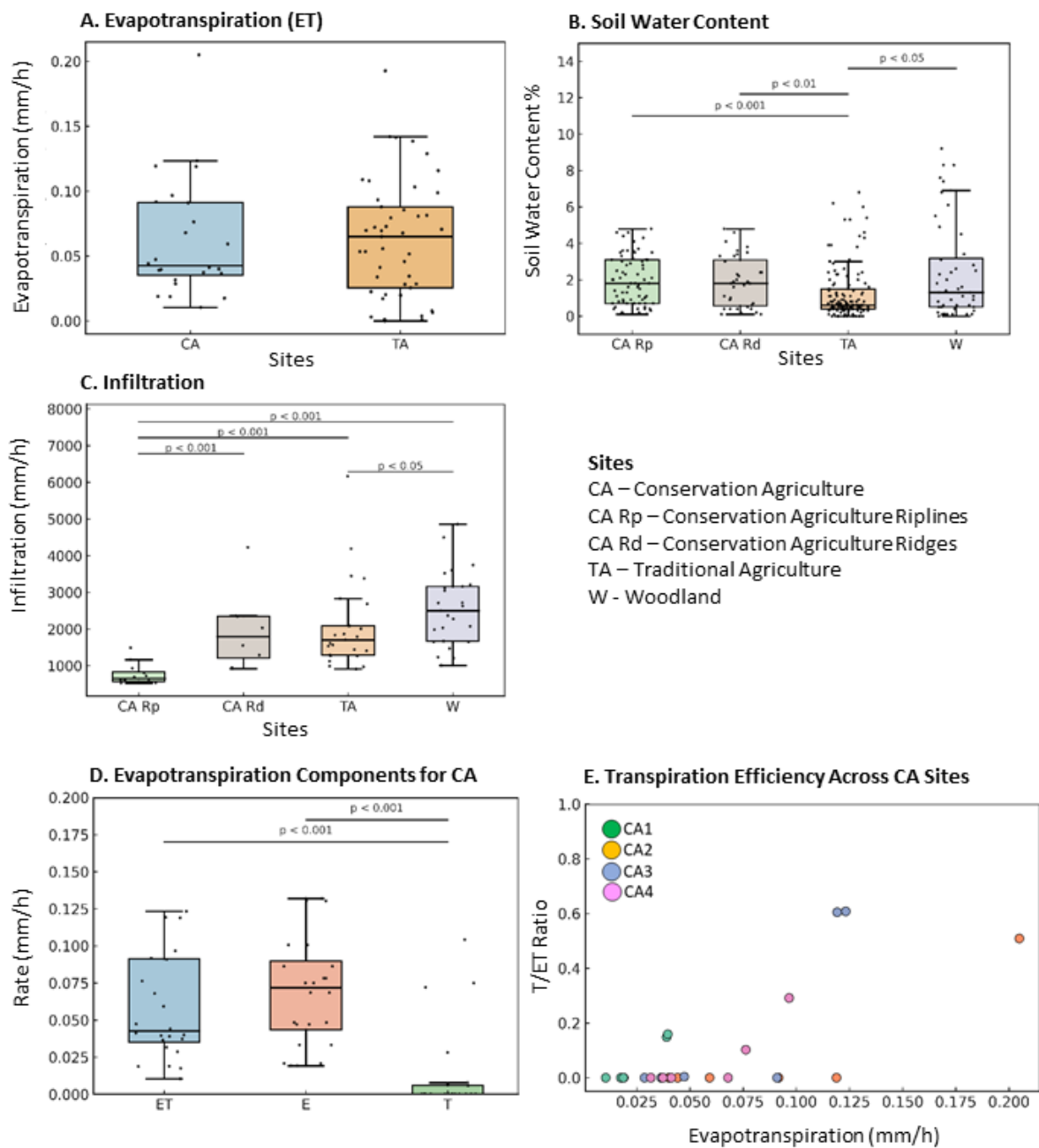
**Figure A3:** Schematic representation of chamber-based measurement of evapotranspiration, showing total water flux within the chamber as the sum of evaporation from the soil surface and transpiration from the plant. Soil evaporation outside the chamber is shown for reference. The setup enables partitioning of evapotranspiration components under field conditions.

### A3 Results and Discussion

Conservation agriculture significantly influenced the key parameters of soil water dynamics for smallholder farmlands under drought conditions. Notably, riplines in conservation agriculture, exhibited a 63.68% increase in soil water content (Cohen's  $d = 1.30$ , very large effect,  $p < 0.001$ ) and reduction in infiltration by 62.74% (Cohen's  $d = -2.45$ , very large effect,  $p < 0.001$ ) relative to traditional agriculture. In comparison to woodland, infiltration was reduced by 70.03% (Cohen's  $d = -2.82$ , very large effect,  $p < 0.001$ ) (Figure A4B-C). Reduced infiltration recorded may enhance plant water availability, assuming they slow percolation losses and promote greater moisture retention in the root zone (Liu et al., 2023). As sandy soils predominantly experience extremely high infiltration (Liu et al., 2019), the observed reduction by riplines, though notable, remained high ( $\sim 900\text{mm/h}$ ) and continues to limit plant water availability. Moreover, the results also directs the attention towards the combined effect of minimum soil disturbance, partial soil cover and spatially controlled planting

that could influence soil water content, consequently, enhancing plant water availability (FAO, 2014; Ngoma et al., 2021). Furthermore, mulching and crop residue retention likely contributed to improved soil aggregation and surface stability, reinforcing the influence of conservation agriculture on soil water dynamics (Selvakumar & Sivakumar, 2021; Siyambango et al., 2022; Stagnari et al., 2010). These improvements may suggest a potential legacy effect of long-term implementation of conservation agriculture (Grahmann et al., 2022).

Further investigations on soil properties analysis revealed that, compared to woodlands, both conservation and traditional agriculture showcased a significant reduction in SOC ( $p < 0.05$ ). This pattern aligns with well-documented SOC losses following land-use change, where conversion from woodland to agriculture has been shown to reduce SOC in Northern Namibia (de Blécourt, 2018). In addition, conservation agriculture significantly differed in soil pH by 15.32% (Cohen's  $d = 4.08$ , huge effect,  $p < 0.05$ ) and had a reduced sand% of 5.11 (Cohen's  $d = 4.08$ , huge effect,  $p < 0.05$ ) relative to woodland. When compared to traditional agriculture, conservation agriculture did not induce statistically significant results, but still exhibited a small increase in water holding capacity by 1.5% (Cohen's  $d = 0.31$ ) and represented a moderately better soil with a reduced sand% of 2.11 (Cohen's  $d = 0.74$ ). These effects could be associated with aggregate stabilization and integration of crop residues associated with mulch-based systems (Abdallah et al., 2021; Cárcelos Rodríguez et al., 2022). The results likely reflect a shift in soil's functional porosity and aggregation, promoting enhanced water retention and slower infiltration (Bescansa et al., 2006; Corsi & Muminjanov, 2019). Moreover, structural interventions such as riplines, improve rooting conditions and modify soil pore architecture, thereby enhancing localized water retention (Abdallah et al., 2021; Bescansa et al., 2006; Cueff et al., 2021; Kassam et al., 2022). The improvements in key soil water dynamics parameters under riplines indicate that the conservation agriculture management practices play a critical role in enhancing dryland agriculture, beyond the advantages conferred by inherently favorable soil conditions.



**Figure A4:** Effects of land-use systems on Evapotranspiration (ET), Soil Water Content and Infiltration (A-C). Partitioning of evapotranspiration into evaporation (E) and transpiration (T) under conservation agriculture and the discourse of transpiration efficiency across sites (D-E).

Regardless of these pronounced shifts in top soil moisture, total evapotranspiration (ET) rates did not differ significantly between conservation and traditional agricultural systems (Figure A4A). While conservation agriculture improved soil moisture availability, this water was not efficiently utilized by crops. In sandy soils, the plant available water is typically limited to 5% of the water holding capacity (Rai et al., 2017; Saxton & Rawls, 2006), which may constraint transpiration. Further analysis of ET partitioning under conservation

agriculture revealed that evaporation (E) was the dominant water loss pathway ( $p < 0.001$ ), while transpiration (T) remained consistently low across all sites (Figure A4D-E). Median transpiration efficiency, expressed as the T/ET ratio, was only 0.07, indicating limited biological uptake of retained moisture. This imbalance could be explained by the extreme high temperatures, low soil water content, high infiltration and partial soil exposure (patches) recorded in our study. In addition, the low transpiration rates could also be attributed to the early stomatal closure in response to the below threshold soil moisture levels, a known adaptive trait in pearl millet under drought (Shrestha et al., 2023). This plant behaviour limits water loss but may constrain crop productivity, emphasizing the importance of water availability within the effective root zone. This underscores the need for complementary strategies such as optimized planting density and improved root-zone management to enhance water use efficiency for drylands systems. These findings align with recent work calling for integrated assessments of ET components to improve water use efficiency in dryland systems (Li et al., 2024; Ramezani Etedali et al., 2025).

## **A4 Conclusions**

This study demonstrates that conservation agriculture can substantially improve soil water dynamics in semi-arid regions by increasing soil moisture retention and moderating infiltration losses, both essential for enhancing drought resilience in smallholder agricultural systems. The observed dominance of evaporation over transpiration highlights a critical limitation in water use efficiency that must be addressed to translate water retention gains into crop productivity improvements. In the broader context of climate adaptation and land-use management strategies, field-based evidence such as this contributes to our understanding of how sustainable land-use practices can be tailored to local agroecological constraints. Conservation agriculture, when implemented consistently and contextually adapted, offers a pathway toward more resilient, resource-efficient and ecologically sustainable farming systems in dryland regions. The utility of conservation agriculture as a water-conserving system could be enhanced through the continuous maintenance of mulch (locally sourced), optimizing plant density to enhance canopy cover and location specific application of organic fertilizers (root zone). Future interventions must integrate structural improvements with agronomic strategies that promote root development and ultimately crop water uptake to enhance water use efficiency.

## **Exercises / Group Discussion Questions**

1. How does conservation agriculture help smallholder farmers adapt to drought and water scarcity?
2. Why is managing infiltration important in sandy soils?
3. What are the long-term goals we can achieve through conservation agriculture?
4. Why is it important to measure and understand soil water dynamics in real farming systems?

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The data is available upon request from the corresponding author.

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## **Study B: Soil water dynamics along the Kalahari dune transects in northern Namibia**

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*Extended abstract (manuscript in preparation)*

## **B1 Introduction**

The Kalahari dunes represent one of the most extensive aeolian landscape in southern Africa (Wang et al., 2007), characterized by a repeating sequence of three main topographic positions, dune crest, slope and interdune, that together define a longitudinal dune-interdune toposequence (Jolivet et al., 2022; Lancaster, 1981). In the Kavango region, the Kalahari dunes extend predominantly in a northeast-southwest direction and rise only a few meters above the surrounding interdunes, with local relief differences reflecting variations in landscape age and erosion history (Garzanti et al., 2022; Lancaster, 1988). The present dune morphology is a legacy of late Pleistocene to Holocene wind activity (Thomas & Shaw, 1991), during which aeolian transport accumulated sand along crests while finer particles and occasional surface runoff settled in interdune hollows, gradually smoothing the dune relief (Thomas & Leason, 2005). The dune sands are deep, consisting of fine- to medium-grained aeolian material with minimal horizon development and high permeability (Thomas & Wiggs, 2022). A natural gradient in elevation and surface exposure creates distinct micro-environments, where, crests are usually dry and sparsely vegetated with grasses and shrubs, whereas interdunes retain moisture for longer periods, supporting denser woody and herbaceous growth (Burke, 2002; Pröpper et al., 2010). Although the geomorphology and sediment properties of Kalahari dunes are well documented (Wang et al., 2007), quantitative field evidence describing how soil water dynamics differ among crest, slope and interdune positions remains scarce. This study therefore investigated how soil water dynamics vary along the dune toposequence in northern Namibia, focusing on the differences in infiltration, evaporation and soil water content.

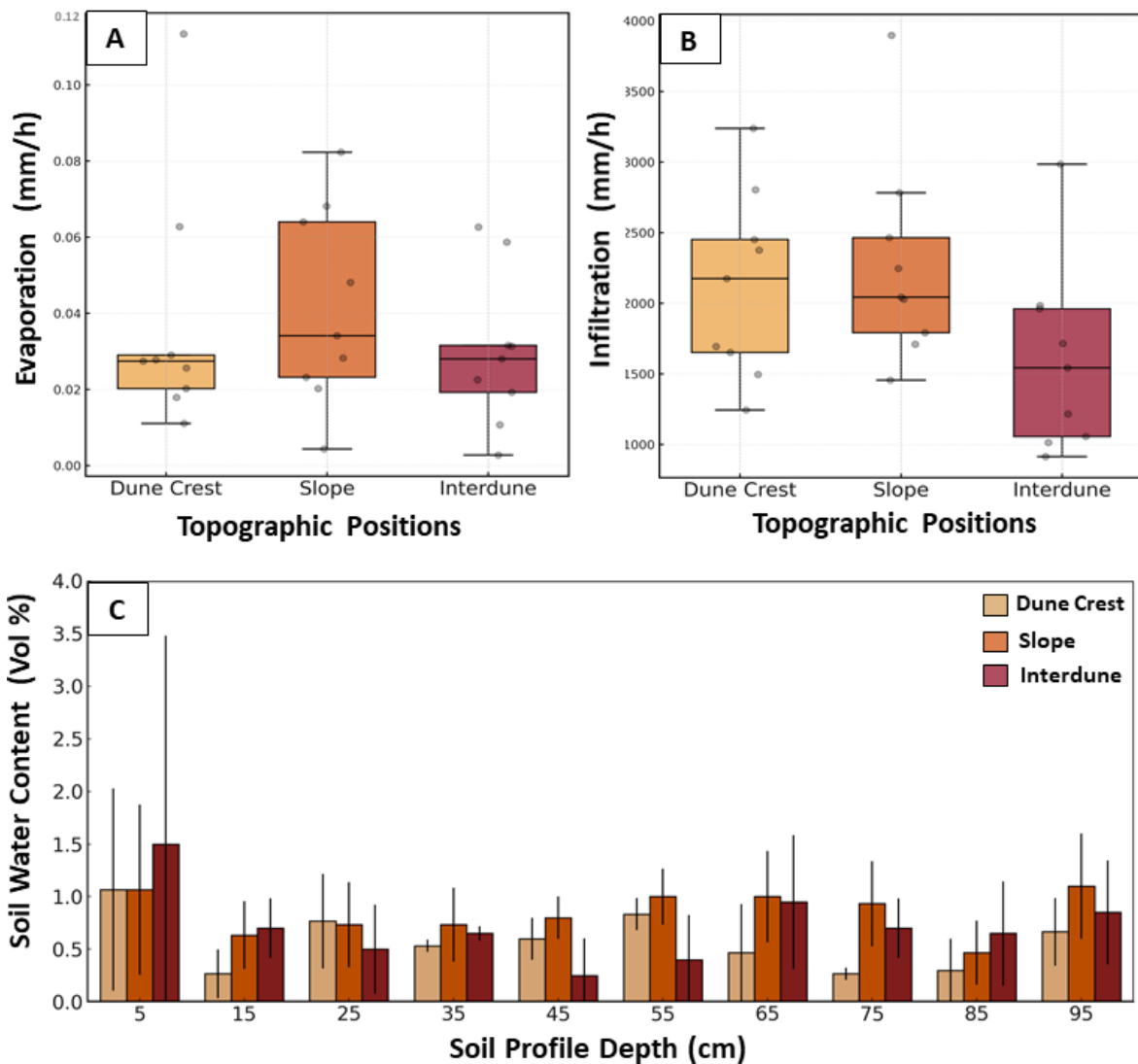
## **B2 Material and Methods**

Field investigations were conducted in March 2024 across three selected dune transects in the Kavango region of northern Namibia. Each transect had three distinguishable topographic positions: interdune, slope, and dune crest, chosen for their geomorphic similarity and accessibility. Soil water dynamics were assessed through the measurements of infiltration, evaporation and soil water content. Infiltration was measured using a modified double-ring infiltrometer equipped with an automated pressure sensor logging at one-second intervals,

with three replicate measurements per site. Evaporation was measured using a closed chamber method, three replications per day per site, repeated for three consecutive days, recording relative humidity at three second intervals over 300 seconds. Soil water content was measured parallel to each chamber using a time domain reflectometry (TDR) sensor. A total of nine soil profiles were excavated up to the depth of 100 cm and segmented into depth intervals of 0-10, 10-20, 20-60 and 60-100 cm. At each depth interval, soil water content was measured and four undisturbed cores were collected for bulk density and related physical property analyses. Mixed topsoil samples from 0-10 and 10-20 cm were taken from the four cardinal directions for chemical analysis. Additionally, observations on vegetation, surface features such as crust formation and notable fire effects were documented in a profile log alongside the profile analysis. All samples were air-dried in Namibia and subsequently transported to Germany for laboratory processing.

### **B3 Results and Discussion**

Evaporation, infiltration and soil water content showed statistically no significant differences among dune crest, slope and interdune positions ( $p > 0.05$ , Figure B1). Evaporation rates remained uniformly low across positions and infiltration exhibited substantial within-position variability without a significant topographic effect (Figure B1A-B). Soil water content along the profile (5-95 cm) also showed no significant differences among positions (LME,  $p > 0.05$ , Figure B1C). Despite the absence of statistically significant effects, several large effect sizes (Cohen's  $d$ ) may suggest meaningful contrasts that may not be captured with the available replication. Infiltration was 25-30% lower in interdunes compared to crest and slope positions, corresponding to large effect sizes ( $d = 0.80-0.96$ ). At the surface (5 cm), soil water content in interdunes was approximately 40% higher than in crest and slope positions ( $d \approx -0.31$  to  $-0.33$ ), while crest and slope showed identical mean values. The absence of statistically significant differences indicated that soil water dynamics did not vary among dune crest, slope and interdune positions, however, the non-significant effect sizes revealed tendencies toward lower infiltration and higher near-surface soil water content in interdunes suggesting that these areas may function as localized zones of hydrological accumulation.



**Figure B1:** Results of evaporation (A,  $n = 9$ ), infiltration (B,  $n = 9$ ) and soil water content (along the soil profile,  $n = 3$ ) across dune crest, slope and interdune positions.

In northern Namibia, Kalahari dunes are comparatively low in relief relative to other sections of the Kalahari mega-transect and are characterized by shallow, low lying interdunes (Lancaster, 1988; White et al., 2015). Over time, these interdunes experienced reduced wind exposure and consequently accumulated finer sediments (Gadal et al., 2022; Lancaster, 1988; Thomas, 1988). Their low relief allowed infiltrated precipitation moving laterally through the surrounding dune sands to converge and temporarily accumulate, enabling interdunes to function as small topographic sinks (Garzanti et al., 2022; Stone et al., 2022). In addition, reduced wind exposure and past surface sedimentation gradually modified micro-topography and soil physical properties, conditions that marginally supported short-term moisture retention (Li & Ravi, 2018; Zhou et al., 2017) and facilitated vegetation establishment (Pröpper et al., 2010). Through organic matter inputs and partial shading, plants helped reduce

evaporative losses and subtly modified the near-surface water-holding capacity (Bhattachan et al., 2014; Porporato et al., 2003; Wiggs et al., 1995). Vegetation patterns in the Kalahari reflect these moisture contrasts, where, dune crests typically support sparse grasses and small shrubs, whereas the lower interdunes retain moisture more readily and permit denser growth of woody seedlings, shrubs and seasonal grasses (Burke, 2002; Pröpper et al., 2010). Interdunes may also intermittently retain shallow ponding or elevated soil moisture after intense rainfall events, creating localized zones of increased fertility (Burrough et al., 2015) that enhance seed germination and vegetation establishment (Jolivet et al., 2022). Thus, interdunes may emerge as the most hydrologically responsive elements of the dune transect, despite the overall homogeneity of the sandy substrate.

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## **Study C: Soil water dynamics and yield responses of cowpea under conservation and traditional agriculture in northern Namibia**

*Extended abstract*

## C1 Introduction

Smallholder farming systems in northern Namibia operate under semi-arid conditions where low and erratic rainfall, high evaporative demand and sandy soils constrain crop performance (Shiimi & Uchezuba, 2025). Conservation agriculture has been promoted as a climate-resilient strategy for semi-arid environments because minimum soil disturbance helps maintain soil structure and reduces the degradation commonly associated with conventional tillage, thereby creating more favorable conditions for crop development (Corsi & Muminjanov, 2019; Siyambango et al., 2022). However, severe nutrient limitations remain a persistent constraint and management changes alone may be insufficient to substantially improve yields.

Cowpea (*Vigna unguiculata*) is widely cultivated across northern Namibia due to its heat and drought tolerance, yet its productivity depends strongly on effective symbiotic nitrogen fixation (Ritte et al., 2022). Native rhizobial populations in these sandy soils often show low effectiveness (Sarkar et al., 2023), making inoculation with climate-adapted *Bradyrhizobium* strains a promising approach to enhance nodulation, nitrogen acquisition and grain production (Grönemeyer & Reinhold-Hurek, 2018). Within this context, the present study addresses how conservation agriculture and traditional agriculture influence soil water dynamics and to what extent mulching, combined with climate-adapted *Bradyrhizobium* inoculation, improves biomass production and grain yield in the sandy soils of Mashare, northern Namibia.

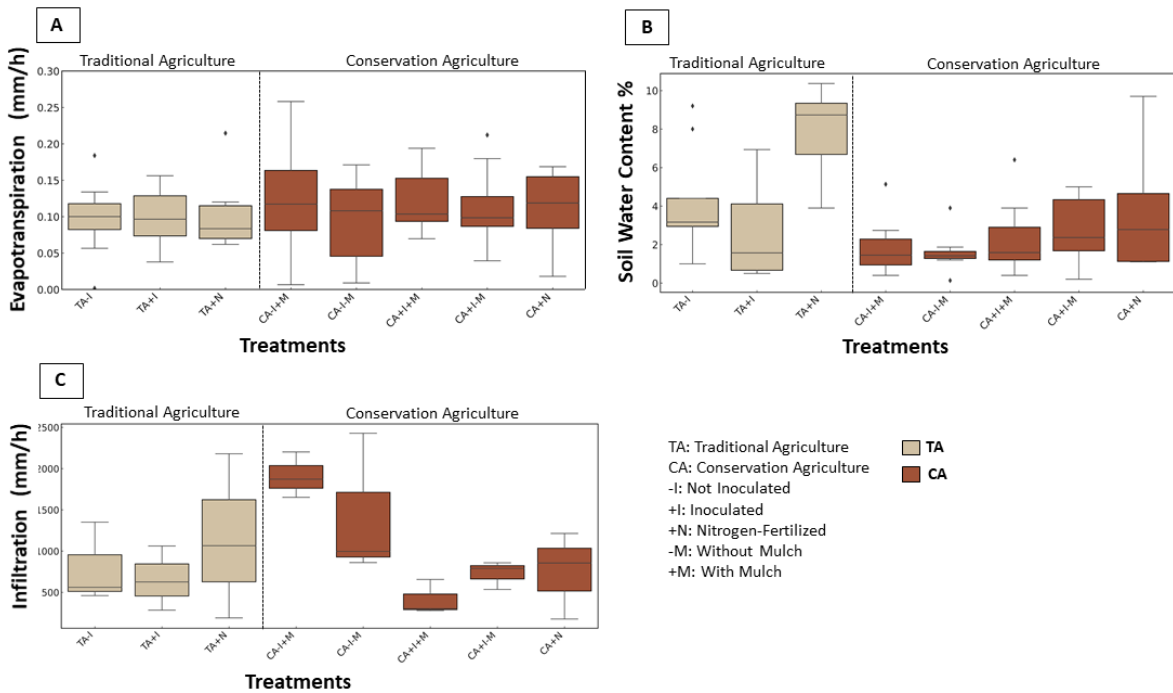
## C2 Material and Methods

Field measurements were conducted in March 2024 at the Mashare Agricultural Development Institute (MADI) in the north-eastern Kavango region of Namibia. The experimental layout comprised plots established under two management systems: traditional agriculture and conservation agriculture. Each plot measured approximately ~ 12 m in width with ~ 2 m spacing between adjacent plots. Within both management systems, three treatment categories were present: inoculated, uninoculated and nitrogen-fertilized, each designed with four unplanted control units per plot. Under conservation agriculture, inoculated plots were further replicated with and without wheat straw mulch. Cowpea varieties Nakhare and Silwana were grown in alternating planted units. Conservation agriculture plots were managed using ox-drawn riplines with

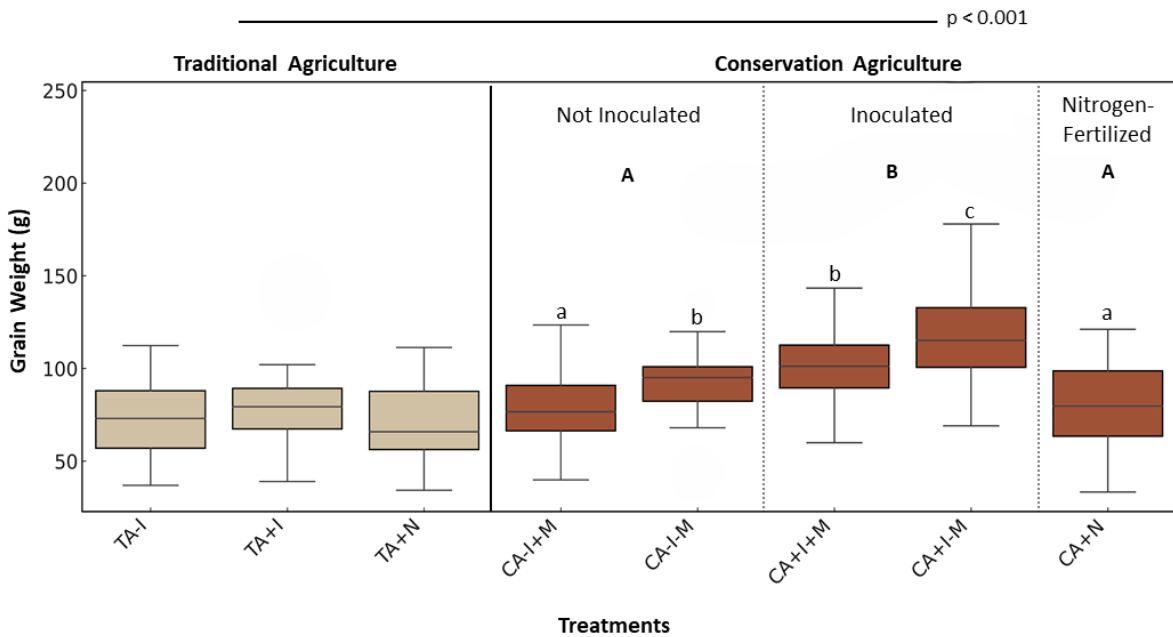
mulch application, while traditional agriculture plots were ripped with a tractor and had no soil cover. *Bradyrhizobium* strain 1-7 (Mashare) was used as the inoculant applied prior to sowing. Soil water dynamics measurements included infiltration using a double-ring infiltrometer, evapotranspiration using a closed chamber method and volumetric soil water content using time domain reflectometry (TDR) sensor. Grain yield data were provided by Rachel N. Iyambo. During the field campaign, plots had been irrigated shortly before measurements and planned unplanted control units were absent, which affected the completeness and consistency of soil water dynamics measurements and data collection. No surface mulch cover was visible during the visit and it was later confirmed that a powdered wheat straw material had been applied (instead of raw wheat straw strands) and subsequently mixed into the soil during field preparation. This limits the reliability of the mulched treatments. The soil water dynamics measurements are therefore reported for completeness (Figure C1), however, the analysis in this study focuses primarily on grain yield, expressed as the wet weight of 100 seeds and the discussion is restricted to the effects of inoculation.

### **C3 Results and Discussion**

Grain weight differed significantly between management systems, with conservation agriculture producing higher yields than traditional agriculture ( $p < 0.001$ , Figure C2). Within traditional agriculture, no treatment differences were significant ( $p = 0.17$ ) whereas, within conservation agriculture, inoculation had a clear and significant effect ( $p < 0.001$ ). Soil water dynamics related effects cannot be evaluated here due to prior irrigation and unreliable mulch conditions.



**Figure C1:** Soil water dynamics across traditional agriculture and conservation agriculture treatments.



**Figure C2:** Grain weight across traditional agriculture (TA) and conservation agriculture (CA) treatments. Black bar above chart highlights the significant difference between TA and CA. Within CA, capital letters denote the significant differences among the; not inoculated (-I), inoculated (+I) and nitrogen-fertilized (+N) treatments, while lowercase letters denote significant differences among mulch categories (-M: without mulch, +M: with mulch).

Minimum soil disturbance, a core principle of conservation agriculture (Kassam et al., 2022), has been shown in northern Namibia to help maintain soil structure and prevent the degradation often associated with conventional tillage (Kudumo et al., 2023), thereby offering a more stable soil environment for crop growth. Against this structural backdrop, the strongest treatment specific response within conservation agriculture was linked to rhizobial inoculation, which enhances nodulation and biological nitrogen fixation in legumes grown on nutrient-poor sandy soils (Becker et al., 2024; Sarkar et al., 2023). By improving nodule formation and increasing the efficiency of symbiotic nitrogen fixation, climate-adapted rhizobial strains strengthen the crop's nitrogen supply, supporting vegetative growth, pod development and ultimately higher grain weight under low-fertility conditions (Kyei-Boahen et al., 2017). The higher yields in inoculated treatments therefore indicate that these climate-adapted strains provided a more effective nitrogen source than the background levels available to uninoculated plants, particularly given that native rhizobial populations in northern Namibia often show limited effectiveness in poor sandy soils (Grönemeyer, 2013). This makes the use of climate-adapted inoculants especially relevant in such environments (Grönemeyer & Reinhold-Hurek, 2018; Luchen et al., 2018). Evidence from similar dryland systems shows that effective inoculation can shift cowpea biomass allocation toward aboveground tissues as nitrogen availability improves (Ezin et al., 2021; Rocha et al., 2019). Overall, the consistent yield advantage of inoculated treatments indicates that strengthened symbiotic nitrogen acquisition, rather than soil management alone, was the key driver of improved grain production in the conservation agriculture system at Mashare. This advantage likely reflects improved nodule function and nitrogen assimilation, enabling inoculated plants to sustain stronger vegetative growth and seed filling compared with the other treatments.

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## **Study D: Cowpea growth response to mulching and inoculation modifying soil water dynamics under simulated drought**

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## D Abstract

Drought constraints cowpea (*Vigna unguiculata*) growth in semi-arid regions such as northern Namibia, where sandy soils intensify water limitations. Management strategies that improve soil water dynamics are crucial for enhancing resilience. While mulching can mitigate evaporative losses, its use is limited by competition for conventional residues, which are often diverted to livestock feed. Namibia's shrub-encroached rangelands, however, provides an alternative source of woody biomass for mulch. This study assessed the effects of wood chips and wheat straw on soil water dynamics and cowpea development under simulated drought. A controlled greenhouse pot experiment was established with sandy soil from the Omusati region, under two irrigation regimes: water optimum (45%) and water stress (20% of maximum water holding capacity), three planting treatments (unplanted; planted; planted + inoculated) and four mulch categories (no mulch; wood chips; wheat straw; a 1:1 mixture). Water stress significantly restricted growth and reproductive success, while mulching buffered these effects. The combined mulch of wood chips and wheat straw reduced total water input by 14.9%, while improving water use efficiency (↑ 233.3%), transpiration (↑ 262.9%), leaflet number (↑ 55.0%), stem height (↑ 11.7%), root and shoot biomass (↑ 68.3% and 45.8%) and harvest index (from 0 to 1.6) compared to the no mulch treatment. Inoculation synergized with mulching, improving biomass allocation and overall development. A phenology-based model predicted pod initiation delays of > 62 days under water stress. Overall, the mixture of wood chips and wheat straw mulch with inoculation represents a promising strategy to improve cowpea growth in semi-arid sandy soils.

**Keywords:** Composite Score Model; Delayed Pod Development; Drought Resilience; Evaporation Barrier; *Vigna unguiculata*

### Synopsis

- Mulching and rhizobial inoculation influence soil water dynamics and cowpea drought response in sandy soils
- Water stress severely constraint growth and delayed pod initiation by over 62 days
- Mixed wood chip + straw mulch improved water use, growth and was the only treatment enabling pod formation

- Inoculation shifted biomass allocation toward shoots but did not overcome reproductive limits under drought
- Combining locally available mulches offers a scalable strategy to enhance cowpea resilience in semi-arid regions

## D1 Introduction

The adoption of leguminous crops in semi-arid regions offer a promising avenue toward sustainable agricultural intensification. Cowpea (*Vigna unguiculata*), increasingly introduced as a rotation crop in dryland farming systems is valued for its nutritional content, drought tolerance and ability to grow in low fertility soils (Becker et al., 2024; de Blécourt et al., 2019; Jeong et al., 2025; Ritte et al., 2022). However, cowpea yields across Sub-Saharan Africa remain well below their potential, primarily due to abiotic stresses such as limited soil moisture and temperature extremes (Ezin et al., 2021; Souza et al., 2024). Drought in particular, is a critical limiting factor, especially when it coincides with sensitive phenological stages such as flowering and pod initiation (Tankari et al., 2021). Water stress during these phases has been shown to impair cell division and expansion, delay phenological progression and drastically reduce both grain and biomass yield (Ezin et al., 2021; Ritte et al., 2022). In addition, drought also disrupts key physiological processes including photosynthesis, stomatal conductance, transpiration and water use efficiency, each contributing to reduced productivity (Hsu et al., 2021; Melo et al., 2025). The cumulative effect of repeated cycles of drought and re-watering, common under rainfed agricultural systems continues to restrict cowpea productivity in arid and semi-arid environments. Therefore, sustainable agriculture in semi-arid regions like northern Namibia requires the development of management strategies that enhance crop performance under drought conditions by improving soil water dynamics (Amami et al., 2021; El-Beltagi et al., 2022; Rafael, 2023; Ramezani Etedali et al., 2025).

One well-established strategy to mitigate soil moisture loss and improve crop performance, is mulching, a fundamental principle of conservation agriculture (FAO et al., 2014). Mulching has shown to reduce surface evaporation (Prosdocimi et al., 2016), improve soil water retention and maintain stable soil temperatures (Kazemi et al., 2019; Thierfelder et al., 2013). However, the adoption of mulching remains limited among smallholder farmers due to the scarcity of available organic mulch materials (Luchen et al., 2018; Valbuena et al., 2012). Crop residues, such as crop straw, are often diverted to

meet livestock feed demands and are therefore unavailable for field application (Han et al., 2020; Mulumba & Lal, 2008; Riseh, 2024). In Namibia, however, large volumes of woody biomass generated from controlling bush encroachment may provide an alternative, as a locally available mulching resource (Díaz et al., 2022; Kariuki et al., 2025; Riseh, 2024; Schick & Ibisch, 2021; Zimmer et al., 2024). The application and combination of locally sourced mulches may improve soil water balance (El-Beltagi et al., 2022) by forming a surface lattice (barrier) that limits evaporation, introduce differential weights to resist wind erosion and fosters soil biological activity (Adetoro et al., 2020; Kader et al., 2017; Kazemi et al., 2019; Nazemi Rafi & Kazemi, 2021). However, the effectiveness of these alternative mulch types remains to be investigated.

In parallel with mulching practices, fostering soil biological activity particularly through enhancing nodulation efficiency in legumes such as cowpea offers an additional strategy to improve plant growth and grain yield (Kyei-Boahen et al., 2017; Martins et al., 2003; Sarkar et al., 2023). Nodulation, which can be fostered through rhizobial inoculation, allows symbiotic biological nitrogen fixation, which supports plant nutrition and development (Yanni et al., 2016). In northern Namibia, low native nodulation efficiency, attributed to poor soil conditions has limited this benefit (Grönemeyer, 2013). However, the use of climate-adapted rhizobial bio-inoculants may enhance nodulation and the associated nitrogen-fixing capacity of cowpea (Becker et al., 2024; Grönemeyer & Reinhold-Hurek, 2018; Luchen et al., 2018). The efficiency of nodules to fix nitrogen, however, is sensitive to water availability, as low soil moisture can compromise nodule function and, in turn, restrict plant growth and productivity (Melo et al., 2025). Therefore, integrating mulching with inoculation may offer a synergistic effect on soil water conservation and plant performance, presenting a promising management strategy for semi-arid systems. Nonetheless, the effectiveness of alternative mulch types and their interaction with inoculation, remains insufficiently understood.

To address these knowledge gaps, this study investigated two core questions:

(1) How do different types of mulching practices and rhizobial inoculation influence soil water dynamics in sandy soils under drought? (2) Do these interventions translate into improved developmental performance in greenhouse-grown cowpea under water stress? A greenhouse pot experiment was established using a three-factorial design incorporating two soil moisture levels (water optimum and water stress), three planting levels (unplanted; planted; planted+inoculated) and four mulching categories (no mulch; wood chips; wheat straw; a combination of both). To compliment empirical observations, a phenology-based composite score modelling approach was

developed to predict delays in pod initiation under water stress. The findings aim to support the development of low-cost, scalable strategies to enhance drought resilience in cowpea cultivation, particularly within sandy, semi-arid environments such as those characteristics of northern Namibia.

## D2 Materials and Methods

The experiment was conducted from May to July 2024 within a controlled greenhouse facility at the University of Hamburg, Klein Flottbek, Germany (53.5615° N, 9.8670° E). Environmental parameters were regulated to stimulate semi-arid growing conditions. Diurnal temperature set points were maintained at 30 °C ( $\pm 2$  °C) during the day and 15 °C ( $\pm 2$  °C) at night, with relative humidity stabilized at 50% ( $\pm 20\%$ ) (Ritte et al., 2022; Seelig et al., 2012; Tankari et al., 2021). A consistent photoperiod (06:00-18:00) was achieved through natural daylight supplemented by artificial illumination as required (Tewolde et al., 2018).

### D2.1 Soil Origin and Plant Material

The soil used in this study is an agricultural topsoil, originating from the UNAM agricultural campus in Ogongo, in the Omusati region of northern Namibia (17°41'08.9"S 15°18'01.1"E, Figure 1 Appendix D). Soil was classified as Eutric Sideralic Arenosols (Aridic) with predominantly sandy texture (Becker et al., 2024), developed on slightly elevated Kalahari sand terraces that are occasionally flooded during summer due to runoff from the Angolan highlands (ANT, 2022; Jürgens et al., 2012). The region experiences a semi-arid climate, characterized by a mean annual temperature of 22.7 °C and an average annual precipitation of 469 mm, the majority of which occurs between December and March, peaking in February (Becker et al., 2024). Table D1 details soil physical and chemical properties of soil used as a substrate in pots.

**Table D1:** Overview of physical and chemical properties of topsoil (0-10 cm) from the Ogongo site, as used in the greenhouse pot experiment.

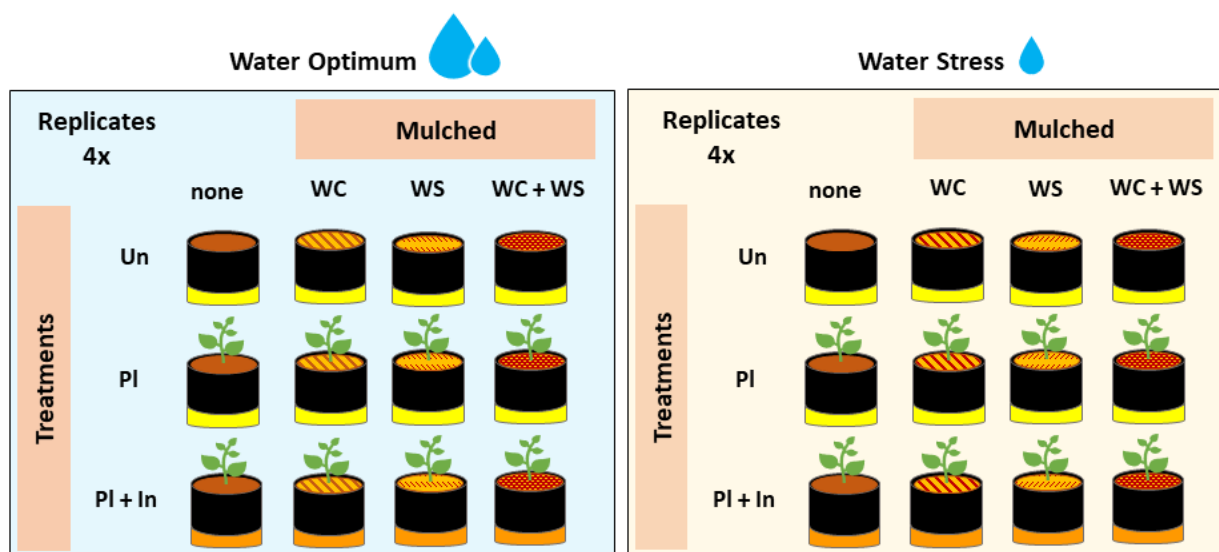
BD (g/cm <sup>3</sup> )	WHC%	SOC%	C/N	pH (H <sub>2</sub> O)	Sand%
1.27	28.13 $\pm$ 0.8	0.30 $\pm$ 0.0	11.64 $\pm$ 0.16	5.38 $\pm$ 0.05	87%

\*Here, BD: Bulk Density, WHC: Water Holding Capacity, SOC: Soil Organic Carbon and C/N: Soil Organic Carbon by Total Nitrogen Ratio.

Cowpea (*Vigna unguiculata*), variety 'Lutembwe', was selected as the model crop for the experiment. Seedlings were prepared in collaboration with the department of Microbe-Plant Interactions, University of Bremen, Germany. Seeds were initially surface-sterilized using a freshly prepared 2.5% sodium hypochlorite solution for six minutes, followed by multiple rinses with sterile distilled water to eliminate residual disinfectant. This procedure aligns with established protocols for optimizing rhizobial colonization and maintaining seed health. Germination was carried out under aseptic conditions on 1% water agar plates, incubated at 30 °C in complete darkness for 24 hours to ensure uniform sprouting prior to transplantation (Becker et al., 2024).

## **D2.2 Experimental Design and Treatments**

Custom made plastic pots (12 cm height, 10 cm diameter) with sealed bottoms were used to prevent drainage and ensure accurate quantification of water dynamics. Each pot was filled with approximately 1000 g of air-dried, sieved (< 2 mm) and homogenized soil. The experimental setup followed a three-factorial design comprising three planting treatments: (i) Unplanted (Un), (ii) Planted (Pl) and (iii) Planted+Inoculated (Pl + In). Each planting treatment was further subdivided into four mulching categories: (a) No Mulch (none), (b) Wood Chips (WC), (c) Wheat Straw (WS) and (d) Wood Chips and Wheat Straw (1:1 mixture, WC+WS). Treatments were maintained under two soil moisture levels: Water Optimum (45% of maximum WHC) and Water Stress (20% of maximum WHC). Each treatment was replicated four times, resulting in a total of 96 experimental pots (Figure D1).



**Figure D1:** Experimental design detailing factorial combinations of planting status and mulching under water optimum and water stress levels. Water optimum and water stress represents two soil moisture levels maintained at 45% and 20% of maximum WHC respectively. Un is unplanted, PI is planted, PI+In is planted+inoculated, none is no mulch, WC is wood chips, WS is wheat straw.

For PI+In planting treatment, germinated seedlings were inoculated with 1 ml of bacterial suspension immediately before sowing. Fresh culture of inoculant strain *Bradyrhizobium* sp. strain 26-nodO was adjusted to optical density of 0.2 at 600 nm with Modified Arabinose Gluconate (MAG) medium instead. This strain had been isolated from nodules of cowpea grown at the UNAM campus Ogongo (Sarkar and Reinhold-Hurek, unpublished). The germinated seedlings of PI (planting treatment) were treated with 1 ml of sterile liquid MAG medium. Mulches were applied at a uniform thickness of 2–3 cm immediately after initial watering. During transplanting seedlings, all pots were irrigated to 60% of maximum water holding capacity to standardize soil moisture conditions (Ritte et al., 2022). Throughout the experiment, soil moisture was monitored and maintained by weighing each pot every fifth day and the volume of water added to restore the target water holding capacity was recorded as the Total Water Input (Boyacı et al., 2024). To ensure plant survival and avoid phosphorus deficiency 100 kg/ha granulated superphosphate with 18% phosphorus pentoxide was added to each pot at the beginning of the experiment (Becker et al., 2024; de Alencar et al., 2025).

The experiment was conducted over an 84-day period, spanning the major developmental stages of cowpea: early vegetative, late vegetative, flowering and pod initiation and development for one crop cycle. Termination occurred at the onset of the reproductive phase, marked by visible pod elongation but prior to seed filling. Physiological measurements were taken at 10-day intervals, including leaflet number, node count and stem height (cm). At harvest, total

biomass was determined by quantifying weights (g) of roots, shoots and pods. Dry biomass (g) of roots, shoots and pods were determined after oven drying at 60 °C (Tankari et al., 2021).

## D2.3 Data Analysis

Linear mixed-effects model (LME) was applied to evaluate differences among treatments (Schielzeth et al., 2020), where, soil water levels, planting treatments and mulch categories were considered as fixed variables and replicates as a random factor to account for spatial variation. For phenological evaluations, the model in addition included day as a fixed variable. At distinct developmental stages ANOVA was applied to evaluate differences at planting and at treatment levels. Model assumptions were confirmed by visual inspection of the model residual (variance homogeneity) and q-q plots (normality). Tukey's HSD test was employed for post-hoc pairwise comparisons among mulching treatments. Data analysis was performed using R version 2024.12.1 Build 563.

### D2.3.1 Calculations

Water use efficiency (WUE) was calculated following (Jones, 2004; Kirkham, 2005) (Eq. 1):

$$\text{WUE} = \text{Total Above Ground Biomass (g)} / \text{Total Water Input (L)}$$

Here, Total Above Ground Biomass is the sum of shoot and pod dry weight and Total Water Input refers to the total amount of water added over the course of the experiment to achieve the target WHC.

Transpiration (T) was calculated as (Choi & Shin, 2020; Cirelli et al., 2012; Jo & Shin, 2021) (Eq. 2):

$$T = \text{Total Water Input (ml)} - \text{Mean Evaporation Unplanted Treatment (ml)}$$

Here, Mean Evaporation Unplanted Treatment refers to the equivalent mean of Unplanted treatment category.

Transpiration Efficiency (TE) in relation to pods was calculated with (Grégoire et al., 2024; Vadez & Ratnakumar, 2016) (Eq. 3):

$$\text{TE}_{\text{pod}} = \text{Pod Biomass (g)} / \text{Transpiration (ml)}$$

Here, Pod Biomass refers to the dry weight of pods and Transpiration was calculated based on Eq. 2.

Harvest Index (HI) was calculated following (Chen et al., 2021; Raboin et al., 2025) (Eq. 4):

$$HI = (\text{Pod Biomass (g)} / \text{Total Above Ground Biomass (g)}) * 100$$

Here, Pod Biomass refers to the dry weight of pods and Total Above Ground Biomass is the sum of shoot and pod dry weights.

### D2.3.2 Pod Initiation Prediction Model for Water Stress Treatments

To establish a phenological benchmark for pod initiation, physiological data collected under water optimum conditions were standardized using z-scores (Di Paola et al., 2023; Kerry et al., 2024). Day 54 was selected as the reference point, as it marked the earliest observable pod initiation across water optimum treatments. Given the absence of statistically significant differences among water optimum treatments, all replicates were pooled to compute the mean ( $\mu$ ) and standard deviation ( $\sigma$ ) for each physiological trait: number of leaflets (L54), node count (N54) and stem height (S54). Individual observations ( $x$ ) were then transformed into z-scores using the formula:

$$z = (x - \mu) / \sigma$$

To obtain an integrated phenological indicator, a composite z-score (CS) was calculated by averaging the individual z-scores across the three traits:

$$CS_{wo} = (Z_{L54} + Z_{N54} + Z_{S54}) / 3$$

This composite score served as a single, unitless index representing overall developmental performance under optimal water conditions. The mean composite score under water optimum conditions was standardized to 0.0 and used as a developmental threshold for evaluating deviations under water stress treatments.

To track phenological progression under water stress conditions, composite z-scores were similarly computed at four time points: day 54, 64, 74 and 84. For each measurement, the same water optimum derived mean ( $\mu_{wo}$ ) and standard deviation ( $\sigma_{wo}$ ) were used.

$$z = (x - \mu_{wo}) / \sigma_{wo}$$

$$CS_{ws54} = (Z_{L54} + Z_{N54} + Z_{S54}) / 3$$

$$CS_{ws64} = (Z_{L64} + Z_{N64} + Z_{S64}) / 3$$

....

To estimate the timing of pod initiation under water stress, linear regression models were then fitted for each treatment using composite z scores as the dependent variable and time ( $t$ ) as the independent variable. Data from water

stress treatments were used for this analysis. For each treatment, the regression equation was:

$$CS_{ws} = a*t + b$$

Where,  $CS_{ws}$  is the composite score for water stress treatment,  $t$  is the time point (day),  $a$  is the slope (rate of phenological progression) and  $b$  is the intercept. The fitted regression lines were then extrapolated to identify the day at which the composite score would cross the threshold value of 0.0, indicating predicted pod initiation under water stress. The predicted day of pod initiation was calculated by solving the regression equation for  $CS_{ws} = 0$ :

$$t = - b/a$$

This yielded a treatment specific estimate of pod initiation timing relative to the developmental trajectory defined under water optimum conditions.

## D3 Results

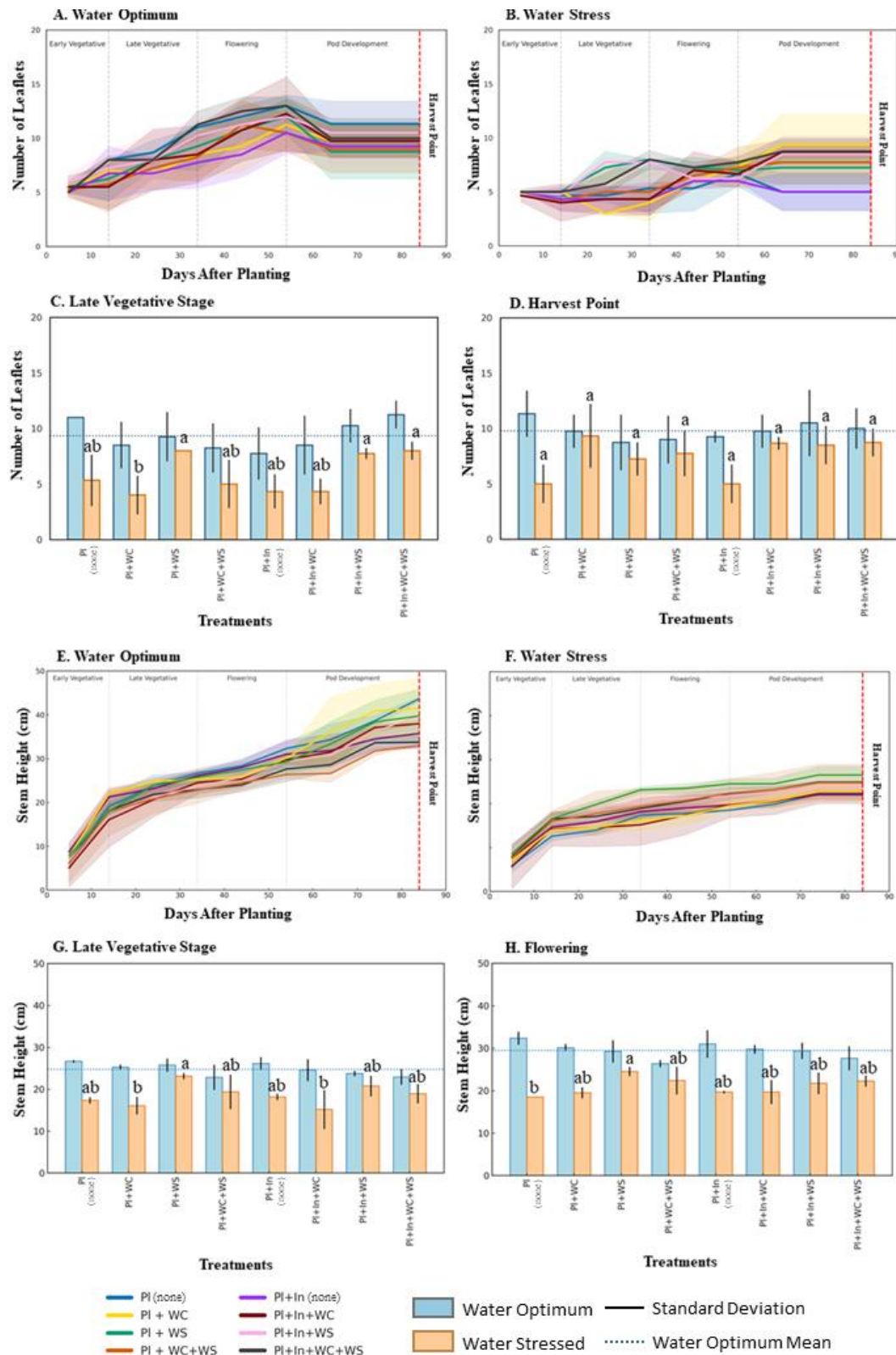
Total water input to achieve target water holding capacity differed significantly between soil moisture levels, with water stress having lower values compared to water optimum ( $p < 0.001$ ), confirming the effectiveness of the imposed irrigation strategy in limiting water availability across water stress treatments (Supplementary Material).

### D3.1 Phenological Variations and Trends

Under both, water optimum and water stress, leaflet number increased significantly over time (LME,  $p < 0.001$ , Figure D2A-B). The leaflet number under water optimum increased at a higher rate (slope mean = 0.052 number/day) compared to water stress (slope mean = 0.035 number/day). One-way ANOVA analysis at distinct phenological stages revealed statistically no significant difference under water optimum at planting and treatment levels. Whereas, under water stress, at the late vegetative stage (day 34, Figure D2C), ANOVA revealed a significant effect of treatments on leaflet number ( $p < 0.001$ ). By the flowering stage (day 54), treatment differences were no longer significant ( $p > 0.05$ , convergence in leaflet number) and at harvest point (day 84) ANOVA again showed a significant treatment effect ( $p < 0.001$ , Figure D2D). Further the extent of mulching impact at late vegetative stage and at harvest was detailed through the mean deviation shown by each water stress treatment from

the mean leaflet number under water optimum. At late vegetative stage, the smallest mean deviations were observed in *PI+WS* (deviation = 1.0), *PI+In+WC+WS* (1.1) and *PI+In+WS* (1.3). At harvest, *PI+WC* (0.6), *PI+In+WC+WS* (0.9) and *PI+In+WC* (0.9) showed smallest mean deviations. In contrast, *PI* (none) and *PI+In* (none) showed the largest mean deviations at both developmental stages ( $\geq 4.8$ ).

Growth in stem height under water optimum and water stress was significant over the given period of experiment ( $p < 0.001$ , Figure D2E-F). The stem height under water optimum increased at a higher rate (slope mean = 0.273 cm/day) compared to water stress (slope mean = 0.120 cm/day). Under water optimum, one-way ANOVA indicated no significant treatment differences at any developmental stage ( $p < 0.05$ ). Under water stress, results showed treatment differences at early vegetative stage, late vegetative stage, flowering and at harvest ( $p < 0.05$ ). The strongest significant differences were observed at late vegetative and flowering stages (Figure D2G-H). Further analysis revealed, *PI+WS* had comparable performance to water optimum treatments, with the lowest mean deviation (1.5) from water optimum mean, followed by *PI+In+WS* (3.9) at late vegetative stage. During flowering, *PI+WS* showed the least mean deviation from the water optimum mean (4.8), followed by *PI+In+WC+WS* and *PI+WC+WS*, both with a mean deviation of 7.1.

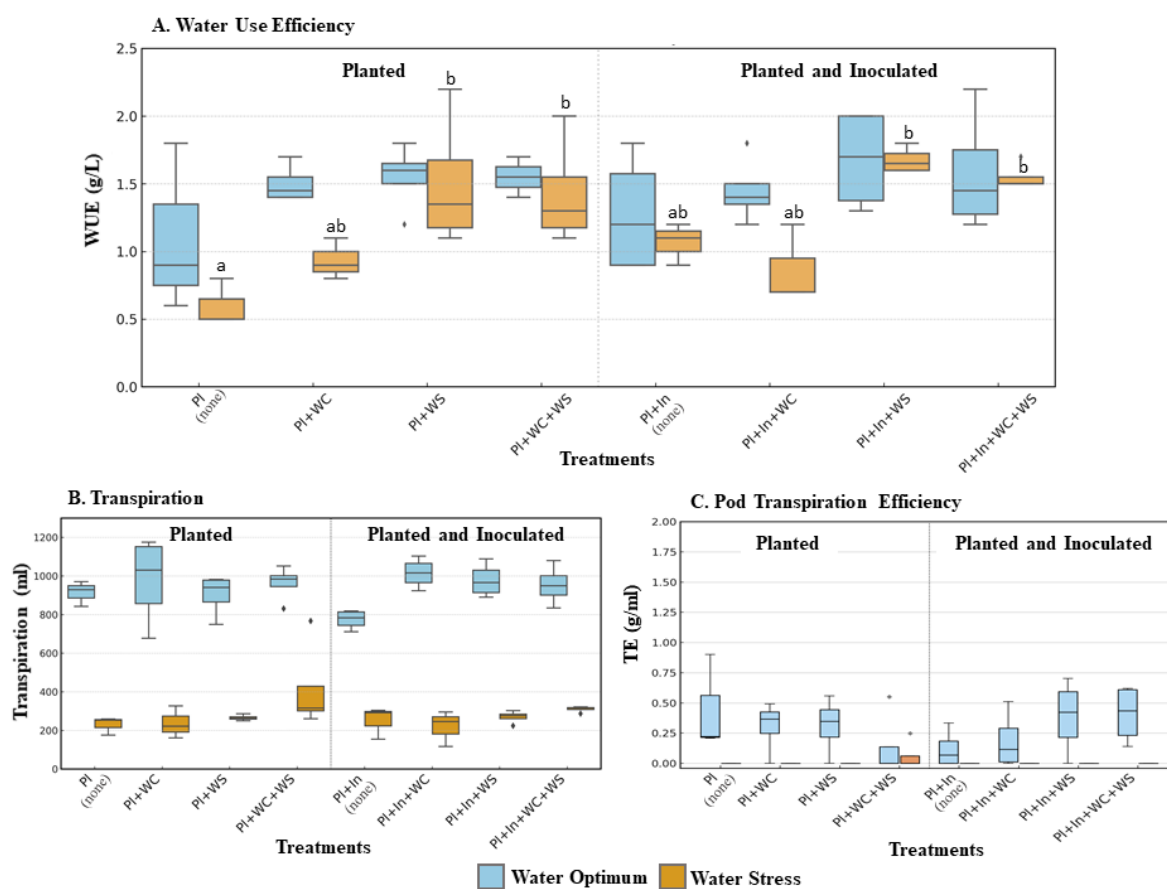


**Figure D2:** Developmental progression in number of leaflets (A-B) and stem height (E-F) over time under water optimum and water stress. Treatments performance for number of leaflets at late vegetative stage and harvest point (C-D) and for stem height at late vegetative stage and flowering (G-H). Lowercase letters showcase the significant difference among water stress treatments. Planting treatments include planted (PI) and planted+inoculated (PI+In). Mulch types include no mulch (none), wheat straw (WS), woodchip (WC) and a combination of both (WC+WS).

### D3.2 Soil Water Dynamics and Biomass Partitioning

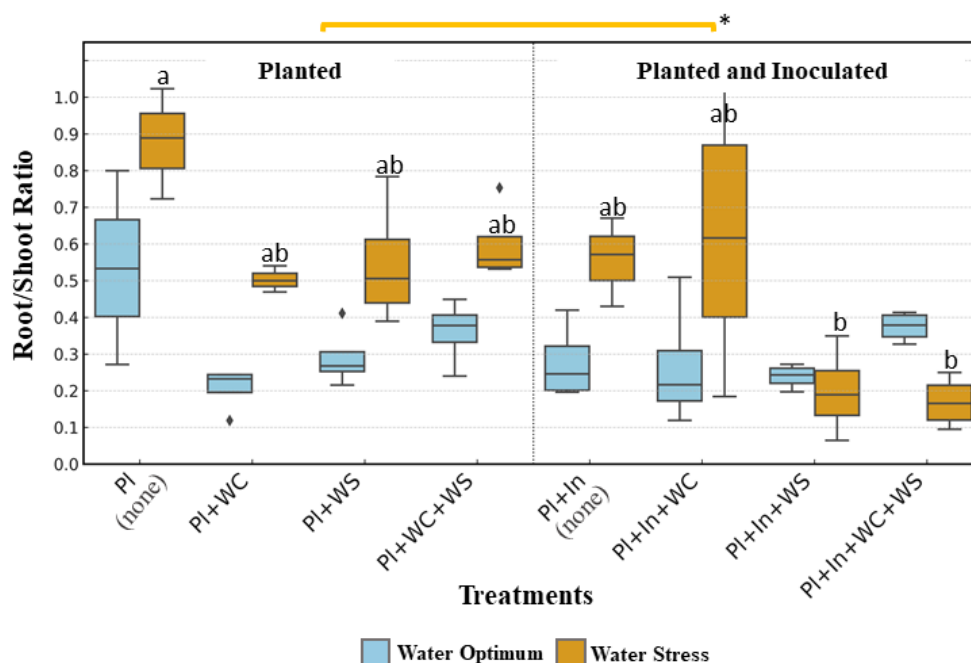
Water optimum treatments had significantly higher WUE than water stress treatments ( $p < 0.01$ ), Figure D3A). Mulching treatments under water stress significantly influenced WUE, where, PI+In+WC+WS, PI+In+WS, PI+WC+WS and PI+WS significantly increased WUE compared to PI (none) ( $p < 0.001$ ). In contrast, treatments with WC alone showed a slight but non-significant increase ( $p = 0.12$ ). The effect of the planting treatment of PI+In was not significant ( $p > 0.05$ ).

In addition, transpiration and pod transpiration efficiency were significantly affected by soil moisture levels ( $p < 0.001$  and  $p < 0.01$  respectively, Figure D3B-C), with higher values observed under water optimum compared to water stress. Planting treatments did not significantly alter transpiration or pod transpiration efficiency ( $p > 0.05$ ). An overall significant effect of mulching was identified (LME,  $p < 0.05$ ), but no pair was significantly different under Tukey post hoc analysis.



**Figure D3:** Effect of treatments on water use efficiency (A), transpiration (B) and pod transpiration efficiency (C) of cowpea under water optimum and water stress. Lowercase letters showcase the significant difference among water stress treatments. Planting treatments include planted (PI) and planted+inoculated (PI+In). Mulch types include no mulch (none), wheat straw (WS), woodchip (WC) and a combination of both (WC+WS).

Root by shoot ratio analysis revealed significant effects of soil moisture levels ( $p < 0.001$ , Figure D4), with values decreasing substantially under water stress compared to water optimum. PI+In planting treatment significantly influenced the root by shoot ratio ( $p < 0.05$ ). Under water stress, pairwise comparisons indicated that treatments combining inoculation with mulching (PI+In+WC+WS and PI+In+WS) significantly reduced root by shoot ratio compared to the PI (none,  $p < 0.05$ ).

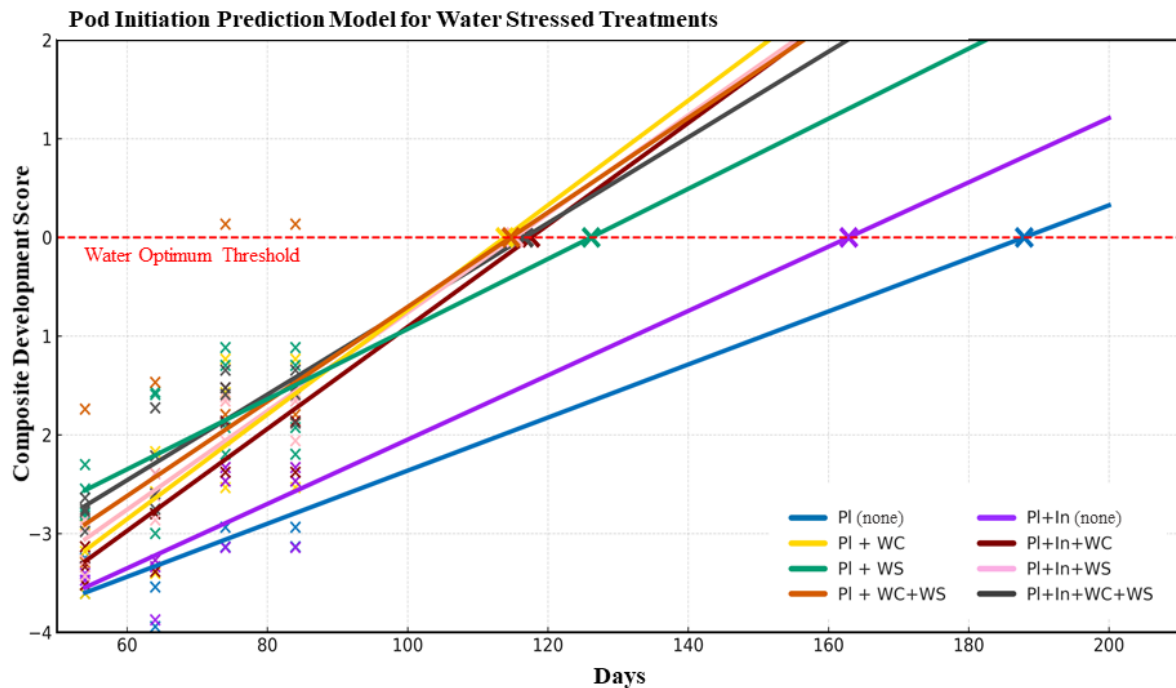


**Figure D4:** Effect of treatments on root by shoot ratio of cowpea under water optimum and water stress. Lowercase letters showcase the significant difference among water stress treatments. Planting treatments include planted (PI) and planted and inoculated (PI+In). Mulch types include no mulch (none), woodchip (WC), wheat straw (WS) and a combination of both (WC+WS). Yellow bar over chart highlights significant difference between planting treatments ( $p < 0.05$ ).

### D3.3 Pod Development Prediction for Water Stress Treatments

Regression lines were fitted to the composite development scores recorded at days 54, 64, 74 and 84 under water stress (Figure D5). All treatments showed positive linear trends and the day at which the development score crossed the pod initiation threshold (composite score = 0.0, based on water optimum treatments performance) was predicted. The predicted pod initiation day mean for the treatments were: PI (187.90), PI+WC (113.85), PI+WS (126.15), PI+WC+WS (114.71), PI+In (162.88), PI+In+WC (117.55), PI+In+WS (115.23), and PI+In+WC+WS (116.65). A two-way ANOVA revealed significant effect of treatments on the slope and intercept ( $p < 0.05$ ), while, post-hoc analysis showed no significant differences among treatments. To validate the

prediction model, pod formation was confirmed by assessing harvest index values (Supplementary Material). Among all water stress treatments, only PI+WC+WS showed a non-zero harvest index in one replicate, aligning with its early predicted pod initiation at day ~80. All other treatments showed a harvest index of zero under stress, supporting the model's prediction that pod formation was either delayed beyond the experiment period or may not occur.



**Figure D5:** Predicted day of pod initiation across water stress treatments based on linear regression of composite development scores at days 54, 64, 74 and 84. Planting treatments include planted (PI) and planted+inoculated (PI+In), with mulch types of no mulch (none), wheat straw (WS), woodchip (WC) and combination of both (WC+WS).

## D4 Discussion

The significant differences observed between the two soil water levels, water optimum and water stress confirm the effective implementation of the experimental design, where, the stressed plants experienced consistent water limitation across all phenological stages, including early vegetative, late vegetative, flowering and pod initiation. These stressed conditions reflect the direct restriction of water availability characteristic of drought or extreme-drought episodes in semi-arid regions such as Namibia (Chen et al., 2025). Such limitations not only reduce total water uptake but also influence subsequent processes such as water-use efficiency, transpiration and overall growth and yield of cowpea.

#### **D4.1 Cowpea Developmental Progression Under Water Stress**

Water stress emerged as the dominant factor constraining cowpea growth and development in this study, with reductions in stem height, node increment, leaflet number and biomass, consistently observed across stressed treatments. However, the interaction with mulching revealed an important moderating effect, as only PI+WC+WS treatment was able to sustain pod production. This finding directly addresses our research question, highlighting that while drought inevitably restricts growth, mulching buffers water scarcity and enables reproductive progression that would otherwise be arrested under drought conditions. In this way, mulching partially compensated for the negative impacts of drought, particularly by sustaining phenological advancement toward pod initiation.

Overall, water stress strongly altered cowpea performance by modifying water use efficiency and transpiration, illustrating how drought reshapes plant's physiological economy of water use and its capacity to maintain growth (Tankari et al., 2021). Under water stress, cowpea plants frequently exhibited relatively higher water use efficiency, that are comparable to equivalent water optimum conditions, probably due to drought-induced stomatal closure (Daryanto et al., 2017). This regulation could have restricted water loss due to transpiration (Liu et al., 2006) and in this study, transpiration was consistently lower under water stress, reflecting reduced water input and potential stomatal control (Anyia & Herzog, 2004; Hatfield & Dold, 2019; Lawson & Vialet-Chabrand, 2019). While this conservative strategy promotes water balance, it can also influence evaporative cooling and CO<sub>2</sub> assimilation (Ayalew et al., 2022; de Souza Silva et al., 2024), ultimately limiting photosynthetic gain and biomass accumulation (Yang et al., 2024). Thus, higher water use efficiency under stress did not equate to improved productivity but instead represented a survival mechanism (Ahmed & Suliman, 2010; Elzopy et al., 2025; Ritte et al., 2022).

Slower growth rates under continuous water stress can be further attributed to the severity of drought (Pejić et al., 2013) on the cellular processes that drive plant development (de Alencar et al., 2025). The growth restrictions extended from vegetative to reproductive development (Ezin et al., 2021). As seen in the present study, reductions in stem elongation and node formation appeared already during the late vegetative stage, consistent with impaired cellular expansion under reduced relative water content (Turk & Hall, 1980). These impairments, including loss of turgor, membrane instability and increased electrolyte leakage, may further explain the slower growth trajectory under continuous water stress (de Alencar et al., 2025). These impairments may restrict cell expansion and increase susceptibility to pathogen attack, leaf

abscission and photosynthetic damage (Adebara et al., 2025; Bhattacharya, 2021; de Alencar et al., 2025; Nkomo et al., 2021). The impacts became even more pronounced during reproductive phases, when drought disrupts chlorophyll production, leaf function, assimilate translocation and ultimately flower and pod retention (Blum, 2018; Bousba et al., 2009; Mendes et al., 2007; Ritte et al., 2022; Seelig et al., 2012). The temporary convergence of leaflet and node number across water stress treatments observed during water optimum flowering (34–54 days) indicated a short-lived prioritization of reproduction even under stress, but the divergence reappeared at pod initiation, underscoring the high sensitivity of reproductive stages to drought (Ngompe Deffo et al., 2024). The flowering and pod initiation stages in this phenological progression of cowpea development is either delayed or would not reach under water limited conditions (Ahmed & Suliman, 2010). Consistent with the composite phenology-based model, which predicted delays of > 62 days for water stress treatments, only PI+WC+WS treached measurable pod development, validating both the model threshold and the buffering effect of mulching.

#### **D4.2 Effectiveness of Mulch Types and Synergies with Inoculation under Water Stress**

Mulching had a strong positive influence on cowpea performance under stress, reflected in enhanced water use efficiency, moderated transpiration and improved developmental parameters across vegetative and reproductive stages. These benefits arise from the ability of surface mulches to reduce soil evaporation, buffer soil temperature fluctuations and maintain higher plant-available water in the rooting zone (Mulumba & Lal, 2008; Prosdocimi et al., 2016; Thierfelder et al., 2013; Valbuena et al., 2012). By stabilizing the soil microclimate and reducing evaporative losses, mulches allow plants to sustain physiological activity for longer periods under drought conditions, resulting in more efficient water use and improved growth (Man et al., 2024; Ramos et al., 2024; Souza et al., 2024). In our study, the combined mulch of wood chips and wheat straw (WC+WS) showed the strongest positive effects among the treatments. Compared with PI (none), PI+WC+WS reduced total water input by 14.9%, improved WUE by 233.3%, enhanced transpiration by 262.9%, increased leaflet number by 55.0%, stem height by 11.7%, root biomass by 68.3%, shoot biomass by 45.8% and improved harvest index from 0 to 1.6. This superior performance likely reflects the complementary properties of the two materials, with wheat straw providing finer coverage that effectively limits

surface evaporation (Wang et al., 2022), while the heavier and thicker wood chips protect against wind displacement and prolong surface retention (Appiah et al., 2023; van Donk et al., 2012). In addition, the differential weights and material properties influence the rates of biological degradation, thereby extending the persistence of mulch on the soil surface while simultaneously contributing diverse nutrients to the soil (Henschke & Politycka, 2016; Klimek et al., 2020; Wang et al., 2025). Together, these qualities may create a more persistent mulch layer that sustains soil water availability and supports growth under stress.

Inoculation further influenced biomass partitioning by enhancing aboveground investment. The root to shoot ratio decreased by 80% in inoculated treatments, that may reflect a shift from root-dominated allocation under water stress toward balanced growth when water and nitrogen availability was improved (Kyei-Boahen et al., 2017; Rocha et al., 2019). When combined with mulching, inoculation indicated synergistic potential, with treatments such as PI+In+WC+WS and PI+In+WS showing relatively higher mean shoot biomass allocation (Nyoki & Ndakidemi, 2014; Tankari et al., 2019). However, these differences were not statistically significant for shoot height, suggesting that while inoculation tended to favor balanced development, the effect was modest and highly variable among replicates. Moreover, the shift in root investment did not translate into improved pod production under water stress, underscoring that reproductive limitations remained dominant (Ezin et al., 2021). This implies that the benefits of inoculation under drought may lie more in sustaining vegetative resilience and physiological efficiency rather than directly enhancing reproductive success and thus grain yield. Consequently, the combined effects of mulching and inoculation point to complementary but partially buffering roles. Their influence on final yield components such as pod initiation remains limited and warrants further investigation.

## **D5 Conclusion**

This study shows that simulated drought severely constrains cowpea growth by reducing water use, transpiration and biomass accumulation, while delaying pod initiation by more than 62 days. Mulching, particularly the combined use of wood chips and wheat straw, proved most effective in conserving soil water, enhancing water use efficiency, increasing biomass and enabling pod formation under water stress. Inoculation further shows trends in shifted biomass allocation toward aboveground growth and when combined with mulching,

reinforced physiological efficiency, although this did not translate into significant improvements in reproductive output. Together, these results demonstrate that water stress was the strongest determinant of growth limitation, but mulching provided a compensatory effect by enabling reproductive progression under stress. While physiological trade-offs such as higher water use efficiency and lower transpiration under water stress are well-established, we show that mulching shifts the developmental outcome under drought by allowing cowpea to reach pod initiation.

Future work should validate these findings under field conditions, where environmental factors such as wind, soil fauna and microbial activity may influence mulch persistence. Synergies between mulching and inoculation also warrant deeper studies, particularly by incorporating parameters such as carbon assimilation and stomatal conductance. In summary, harnessing locally available resources, including wood chips sourced from bush-encroached regions, offers a sustainable pathway to maximize efficiency and resilience in semi-arid farming systems.

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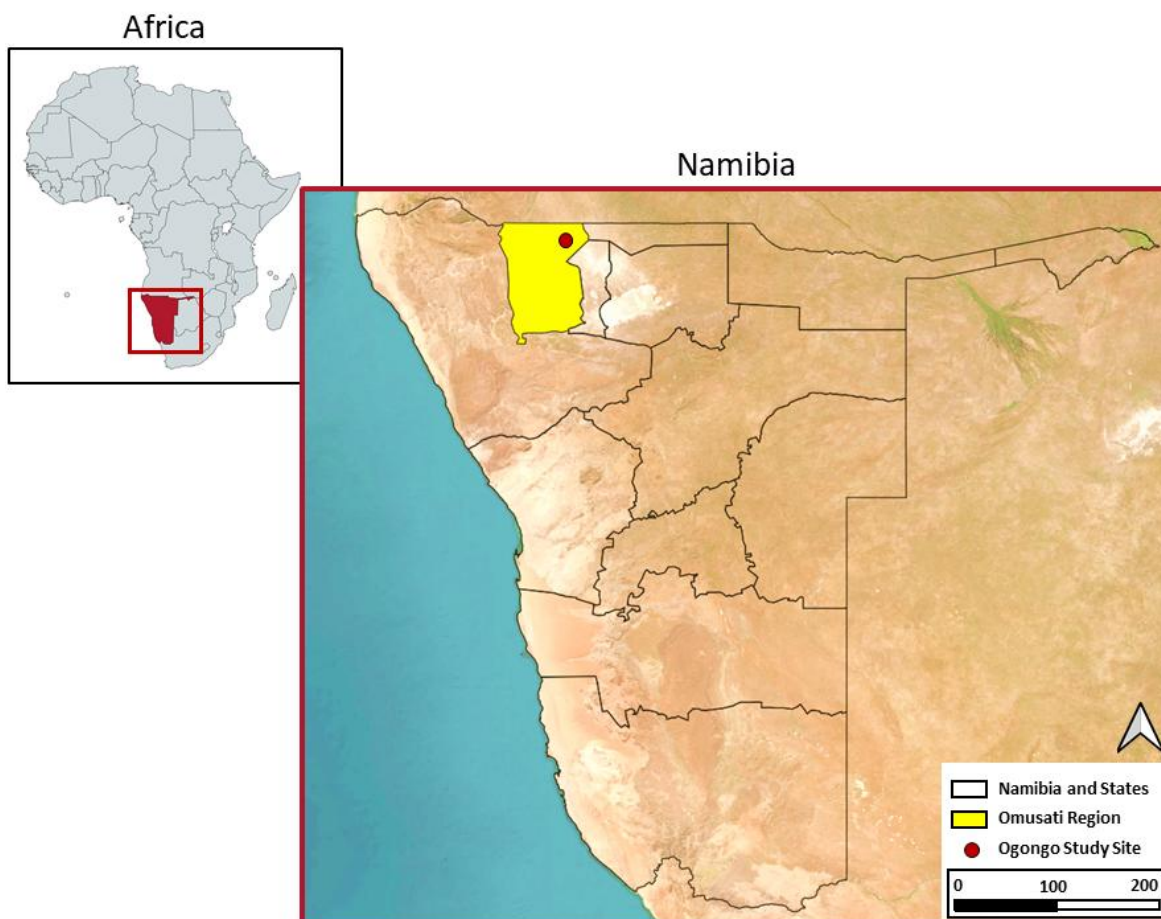
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## D7 Supplementary Material

### *Study Site*

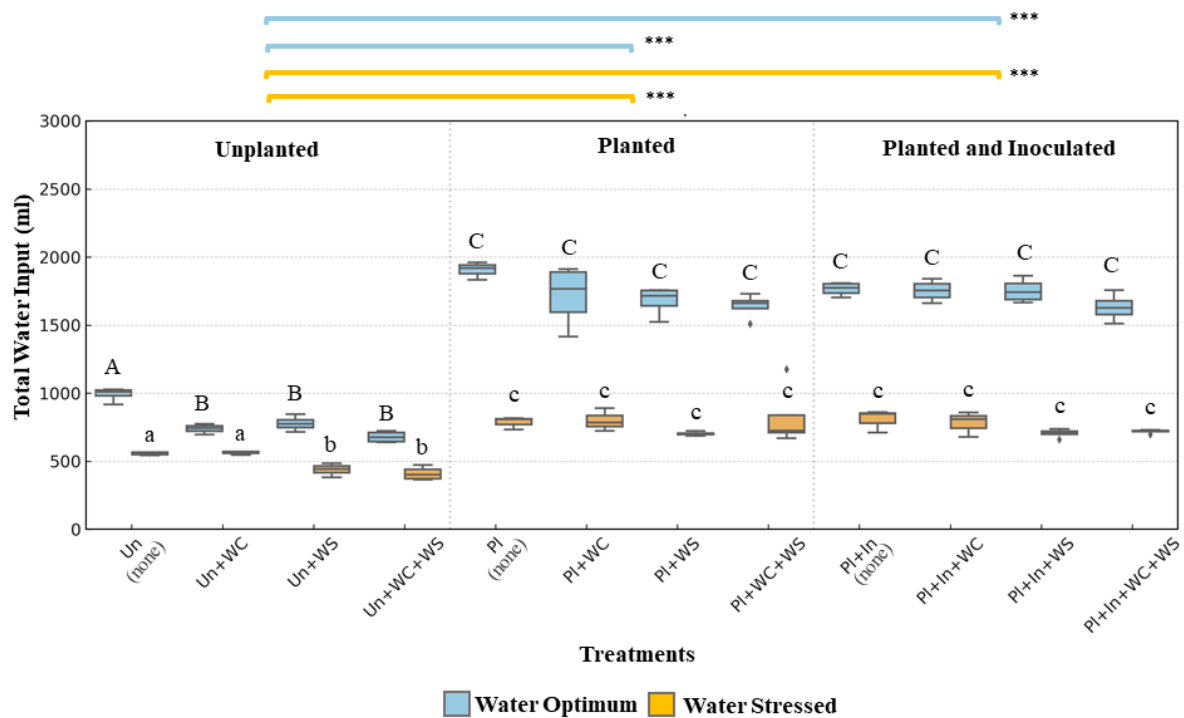


**Figure 1:** Geographic location of Namibia, Africa (MapChart, 2025). The extended map details the spatial region of Omusati highlighting the Ogongo study site in Northern Namibia (QGIS 3.28.3).

### *Total Water Input*

Model estimates showed that water level had a highly significant effect on total water input ( $p < 0.001$ , Figure 2). Under water optimum and water stress, both planting treatments, PI and PI+In exhibited significantly higher water input compared to the Un planting treatment ( $p < 0.001$ ). While, no significant difference was detected between PI and PI+In planting treatments. Mulching treatments demonstrated moderate but consistent effects under both water levels. Under water optimum and Unplanted (planting treatment), all mulched treatments were significantly different than no mulch treatment (none,  $p > 0.05$ ). Under water stress and Unplanted (planting treatment) Un+WS and Un+WC+WS significantly reduced total water input relative to the no mulch

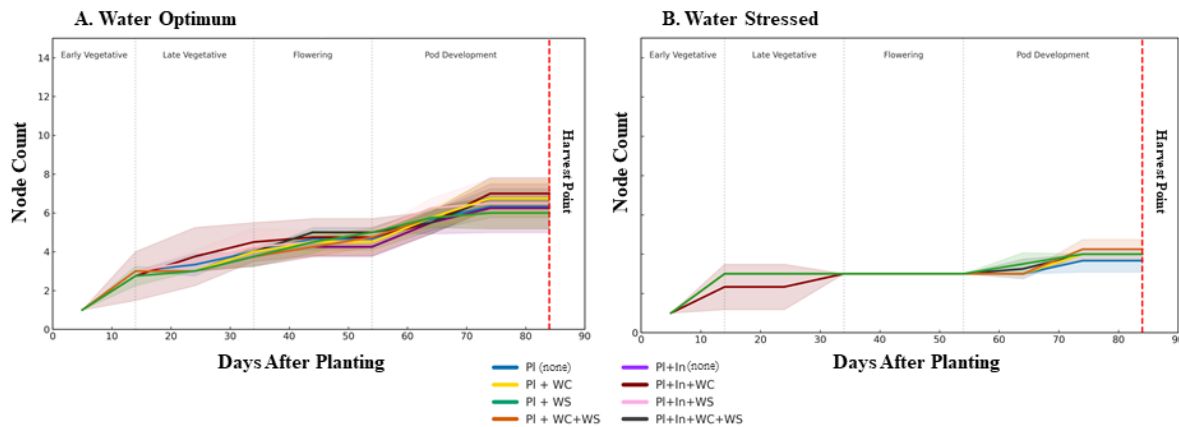
treatment (none,  $p = 0.018$  and  $p = 0.005$ , respectively), whereas Un+WC had no significant effect ( $p > 0.05$ ). Random effects associated with replicates were minor, indicating low spatial variability.



**Figure 2:** Total water input under water optimum and water stress across unplanted (Un), planted (PI) and planted+inoculated (PI+In) planting treatments. Mulch types include no mulch (none), wheat straw (WS), woodchip (WC) and a combination of both (WC+WS). Blue (water optimum) and yellow (water stress) bars with asterisks (over chart) highlight significant differences among planting treatments (\*\*\*) is  $p < 0.001$ ). Uppercase and lowercase letters indicate significant differences among mulch categories under water optimum and water stress treatments respectively.

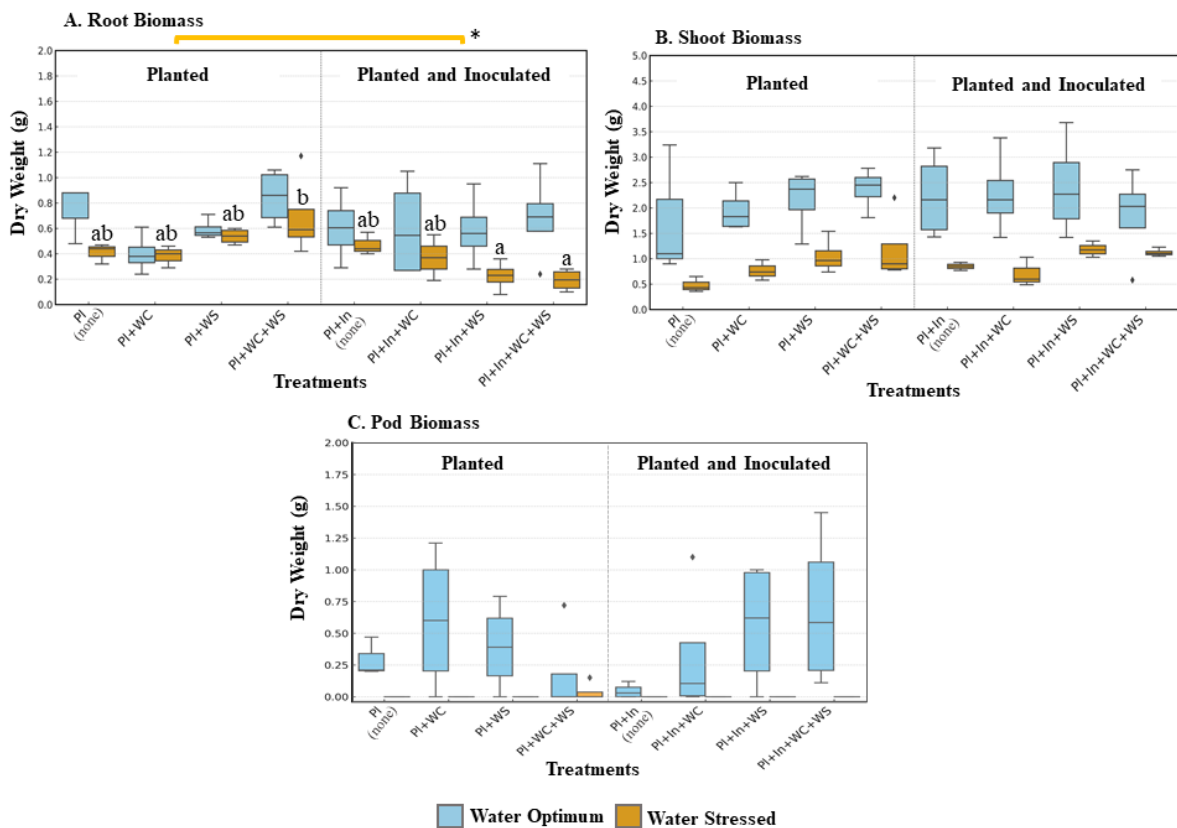
### *Developmental Progression in Nodes*

Node count increased significantly over time under both water optimum and water stress ( $p < 0.001$ , Figure 3). However, the rate of node formation over time was higher under water optimum (slope = 0.064 number/day) than water stress (slope = 0.026 number/day). Overall, while time had a strong effect, treatment-related differences in node development were not statistically evident under either condition.



**Figure 3:** Node count progression under water optimum (A) and water stress (B). Planting treatments include planted (PI) and planted and inoculated (PI+In). Mulch types include no mulch (none), wheat straw (WS), woodchip (WC) and a combination of both (WC+WS).

*Root, Shoot and Pod Biomass*



**Figure 4:** Root (A), Shoot (B) and Pod (C) biomass across treatments. Planting treatments include planted (PI) and planted+inoculated (PI+In). Mulch types include no mulch (none), wheat straw (WS), woodchip (WC) and a combination of both (WC+WS). Yellow bar (water stress) with asterisk over chart highlight significant difference among treatments (\* is  $p < 0.05$ ). Lowercase letters indicate significant differences among mulch categories under water stress (Tukey's HSD,  $p < 0.05$ ).

**Table 1:** Harvest Index (HI)

<b>Treatments</b>	<b>Water Optimum</b>	<b>Water Stress</b>
PI (none)	18.22	0
PI+WC	22.13	0
PI+WS	16.28	0
PI+WC+WS	7.11	1.60
PI+In (none)	2.48	0
PI+In+WC	13.07	0
PI+In+WS	20.13	0
PI+In+WC+WS	28.06	0

**Table 2:** Developmental stages of cowpea (*Vigna unguiculata*) and associated phenological characteristics observed under water optimum.

<b>Developmental Stage</b>	<b>Time Span (Days)</b>	<b>Phenological Characteristics</b>
Early Vegetative Stage	0 - 14	Leaf expansion, root anchorage
Late Vegetative Stage	14 - 34	Canopy growth, stem elongation
Flowering	34 - 54	Buds, blooms, pollination
Pod Initiation and Development	54 - 84	Visible pods, early elongation

## **Study E: Water vapor from deep soil reservoirs as a viable water source for plants in sandy soils**

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## E Abstract

In sandy soils, the formation of a dry soil layer creates a capillary barrier that restricts the upward flow of water, thereby limiting its availability to plants. Under such conditions, the water from deeper soil reservoirs may reach the root zone primarily as vapor. It is currently unknown if plants can utilize this water vapor and if there are management possibilities that could enhance the respective water vapor uptake. This study investigates the potential for water vapor uptake in *Vigna radiata* under controlled drought conditions. Ten-to-fifteen-day old saplings were introduced into columns with sandy soil, that was separated from a water reservoir by a capillary barrier and a root impermeable mesh (50  $\mu\text{m}$ ). Treatments included unplanted and planted columns (with and without mulch), with an additional set of planted columns comparing plant survival in the presence or absence of the water vapor source. Cryo-extraction and liquid water isotopic analysis ( $\delta^2H$ ) of saplings, soil layers (0-5, 5-10 and 10-15 cm) and vapor condensates revealed differential deuterium enrichment, indicating upward vapor flux and plant uptake of water vapor. Plants with access to water vapor source exhibited an extended survival of  $\sim 2.7$  days under drought. Mulching further amplified the effectiveness of vapor availability by 38.2% through reduced surface evaporation, thereby extending the plant survival by  $\sim 4.5$  days, compared to planted treatment with no vapor source. These findings provide evidence that plants can access water from a spatially separated water reservoir under conditions permitting only water vapor movement and suggest that agronomic practices such as mulching could enhance this process in semi-arid regions.

**Keywords:** Deuterium Labelling; Plant Survival, Water Vapor Utilization; Water Vapor Re-Condensation

### Highlights

- *Vigna radiata* saplings survived longer when exposed to a spatially separated water vapor source.
- Mulch reduced surface evaporation while enhancing top soil moisture, influencing plant water availability and survival.
- Differential deuterium distribution across the soil column indicates the upward flux of water vapor originating from the spatially separated deep water reservoir and its potential uptake by saplings.

## E1 Introduction

In sandy soils, the development of a dry soil layer (Balugani et al., 2018) critically disrupts the hydraulic connectivity between deep water reservoirs and the soil surface (Deol et al., 2014), which has direct implications for the plant water access. The dry soil layer characterized by the rapid depletion of pore water (Song et al., 2018) leads to the formation of a capillary barrier that restricts the upward movement of water (Lehmann et al., 2008). In this configuration, the actual evaporating front at the soil surface shifts to the base of the dry soil layer, where water is vaporized and subsequently diffuses upward (Balugani et al., 2018; Wang et al., 2020), before being released into the atmosphere (Sun et al., 2023). As evaporation progresses, this vaporization front retreats further into the soil, deepening the dry soil layer over time (Sun et al., 2016; Wang et al., 2020) and reinforcing the capillary barrier (Deol et al., 2014).

As a result, the deep water reservoirs often remain inaccessible to young plants, particularly during the early stages of growth when the root systems are underdeveloped (Ehleringer et al., 1992; Marcos-Garcia et al., 2024; Ryel et al., 2002). This challenge is further intensified in arid and semi-arid regions, where sandy soils dominate and precipitation is irregular, low in volume and often lost rapidly to surface evaporation rather than percolating deeper into the soil (de Vries et al., 2000; Li et al., 2010; Liu et al., 2021). As the water supply is a major determinant of plant growth (Barrs et al., 1968; Kramer, 1937), restricted moisture availability can result in significant water deficits in plants (Bhattacharya, 2021), particularly under prolonged drought conditions (Zhou et al., 2023).

Existing studies have largely focused on vapor transport through dry soil layers as a mechanism of soil water loss (Balugani et al., 2021; Zheng et al., 2020), particularly in quantifying evaporation from deep water reservoirs under arid and semi-arid conditions. However, there remains a significant gap in understanding whether plants can take up and actively utilize water vapor. Arid and semi-arid regions constitute a substantial portion of the Earth's surface (Balugani et al., 2018) and experience extended dry periods that coincide with the early stages of crop establishment (Marcos-Garcia et al., 2024; Slawin et al., 2024), that may limit the effectiveness of known drought adaptation strategies such as hydraulic lift, deep rooting and osmotic adjustments (Alagele et al., 2021; Oguz et al., 2022; Singh et al., 2021). Therefore it is crucial to investigate mechanisms that may support young plants during these vulnerable phases of development (Golla, 2021; Siyambango et al., 2022).

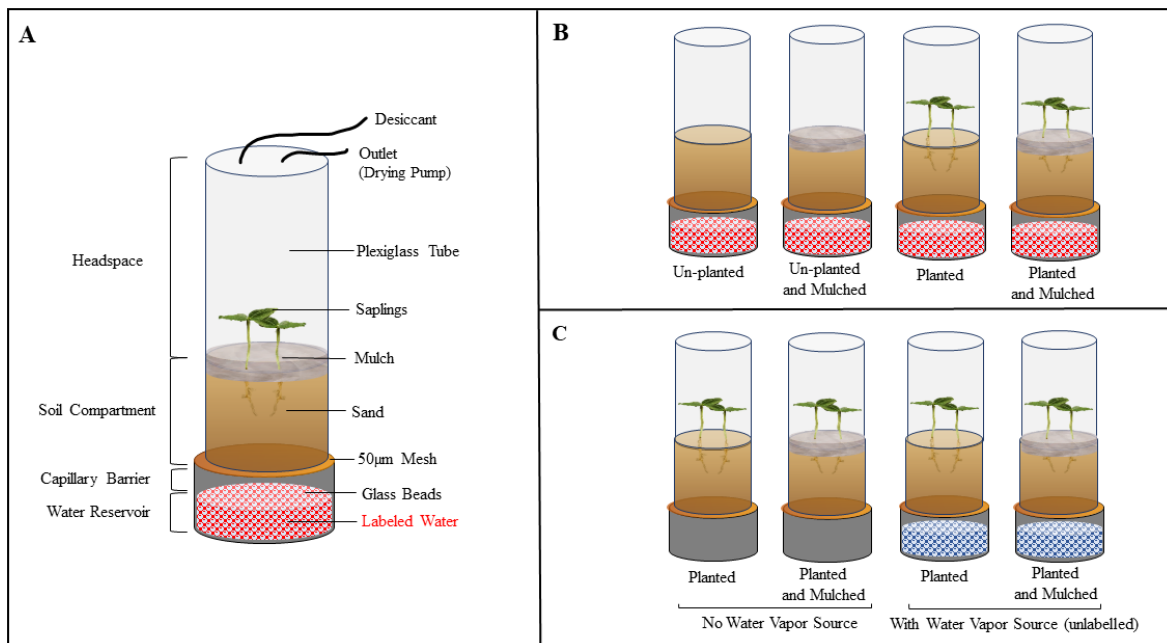
In soil systems with a dry soil layer, where water flow is blocked by capillary barriers, water vapor movement may become the dominant mechanism through which deep source water moves toward the surface (Balugani et al., 2017; Deol et al., 2014; Wang et al., 2020). Recent studies have suggested that under water-limited conditions, plants may absorb condensed water vapor during night or early morning, helping to alleviate diurnal water stress (Bhattacharya, 2021; Wang et al., 2023). Additionally, the presence of surface mulching may influence the surface moisture by reducing evaporative losses and promoting vapor condensation near the root zone (Demo et al., 2024; Ramos et al., 2024). These condensation events are further modulated by diurnal temperature fluctuations in the upper soil layers (Assouline et al., 2013; Mahdavi et al., 2020; Sakai et al., 2009).

To address these gaps, this study aimed to investigate (1) whether plants are able to take up water vapor from the hydraulically decoupled deep soil water reservoir, (2) whether the utilization of water vapor has a physiological relevance to the plant survival under drought conditions and (3) whether this process could be enhanced by an agronomic management strategy, specifically, the application of mulch. To examine these objectives, we designed a column experiment with sand and *Vigna radiata* saplings. *V. radiata* was selected as the model species due to its rapid early-stage growth, high sensitivity to drought during establishment and its relevance as an important leguminous crop in semi-arid regions (Singh et al., 2021), making it suitable for detecting subtle water acquisition mechanisms. The sand compartment was hydraulically isolated from a water reservoir using a capillary barrier and a root-impermeable mesh, permitting only water vapor movement. Treatments were subjected to drought conditions and included both planted and unplanted columns, with and without mulch, along with a vapor-source exclusion control to isolate physiological responses.

## **E2 Materials and Methods**

The experiment used self-constructed plexiglass columns (Figure E1). Each column consisted of a water reservoir, a capillary barrier, a sand compartment and a headspace section. The water reservoir was filled with ~120 ml labeled water (155  $\mu$ l Magnisolv™ Deuterium oxide (99%) in 1.55L tap water), where deuterium acted as a tracer element (Beyer et al., 2018; Osipenko et al., 2023; Peñuelas et al., 2003; Soheli et al., 2021). The water reservoir and the soil compartment were separated by a capillary barrier (~3 cm empty space) and a

root barrier (50  $\mu\text{m}$  nylon mesh). The soil compartment was filled with washed sea sand (99.48% purity with 0% coarse, 61.4% middle and 38.08% fine sand, 7 pH in  $\text{H}_2\text{O}$ , 6.1 pH in  $\text{CaCl}_2$ ,  $\sim 0\%$  volumetric soil water content) at a bulk density of  $1.19 \text{ g cm}^{-3}$ . The headspace was constantly flushed with dry air using a drying pump with cobalt chloride desiccant, maintaining an estimated relative humidity of  $\sim 5\text{-}10\%$ . This setup minimized external water vapor contamination and ensured a stable vapor pressure gradient across the system, assumed to be  $\sim 5.2 \text{ kPa/m}$  (based on  $\sim 100\%$  relative humidity at water reservoir, Supplementary Material). The prepared soil columns were placed in a Poly Klima® Climatic Grow Systems chamber with a constant day-night cycle. The day and night temperature set points were  $30^\circ\text{C}$  and  $15^\circ\text{C}$  respectively. The experimental setup was left undisturbed for a period of seven days.



**Figure E1:** A. Illustration detailing the structural design of the sand column. B. Experimental design including; unplanted (Un), unplanted and mulched (Un+M), planted (PI) and planted and mulched (PI+M) treatments used to investigate the uptake of water vapor (deuterium enriched) by saplings and water vapor contribution to water condensate and at different soil depths. C. Experimental design including treatments used to investigate the physiological relevance of water vapor uptake for the survival of *V. radiata* saplings. Treatments include planted with no vapor source (PI-V), planted and mulched with no vapor source (PI+M-V), planted with a vapor source (PI+V) and planted and mulched with a vapor source (PI+M+V).

The experiment had four treatments (Figure E1B), (1) Un-planted (Un); (2) Planted (PI); (3) Un-planted and Mulched (Un+M); (4) Planted and Mulched (PI+M). A plastic food wrap ( $\sim 12 \mu\text{m}$  thickness) with small pinholes was used as mulch that covered the entire soil surface of the treatment section, consistently applied across all mulched treatments. In addition, a control (planted) column

with normal tap water (unlabeled) was setup for isotopic ratio comparisons. Each treatment was replicated three times. After the experimental period of seven days, sand was sampled from 0-5, 5-10 and 10-15 cm depths. Sand from each layer was first extracted into a separate container and mixed thoroughly to ensure homogeneity and to reduce isotopic ratio bias (Vargas et al., 2020; West et al., 2006). Glass vials were prepared with  $\sim 50$  g soil from each layer. *V. radiata* saplings were extracted with intact shoot, root and leaves. Water condensate at the inner wall of the headspace section (soil column) was collected with a thin tissue paper from PI and PI+M treatments and stored in glass vials. The vials were sealed with Polyseal<sup>®</sup> stoppers to prevent evaporation.

To determine the physiological relevance (survival, time period) of water vapor utilization by *V. radiata*, an additional experiment was conducted under identical experimental conditions. Planted (PI) and planted and mulched (PI+M) treatments (Figure E1C) were replicated three times with and without the water vapor source ( $\sim 120$  ml unlabeled tap water). Evaporation from the water reservoir and sapling biomass were quantified by weighting the reservoir section and saplings at the beginning and end of the experiment, respectively. The experiment ended when the saplings showed visible signs of wilting (Vargas et al., 2020) and the respective time period of survival was recorded.

## E2.1 Water Vapor Extraction and Isotopic Analysis

Water was extracted from soil and plant samples using cryogenic vacuum distillation (Aragufis-Aragufis et al., 1995; Chen et al., 2020; Diao et al., 2022). Samples were heated to 130°C under low pressure and evaporated water was collected in a liquid nitrogen trap (Newberry et al., 2017; Wen et al., 2021). Extraction times were 30-40 min for soil and 45-60 min for plant samples and water condensate (Koeniger et al., 2011; West et al., 2006). Isotope analysis was conducted using a Triple Isotopic Water Analyzer (TIWA-DLT\_EP Los Gatos Research). For enriched water samples,  $\delta^2H$  measurements were within 1.2% of assigned values (ABB, 2017), with a measurement precision of  $\pm 0.4\text{‰}$  ( $1\sigma$ ,  $\delta^2H$ ) and a detection limit of 0.02% excess deuterium, ensuring reliable differentiation between labeled and control samples (ABB, 2021). Isotopic measurements were processed using Liquid Isotopic Water Analyser Post Analysis software with the integrated Spectral Contaminant Identifier to detect and correct potential spectral contamination (LGR, 2016).

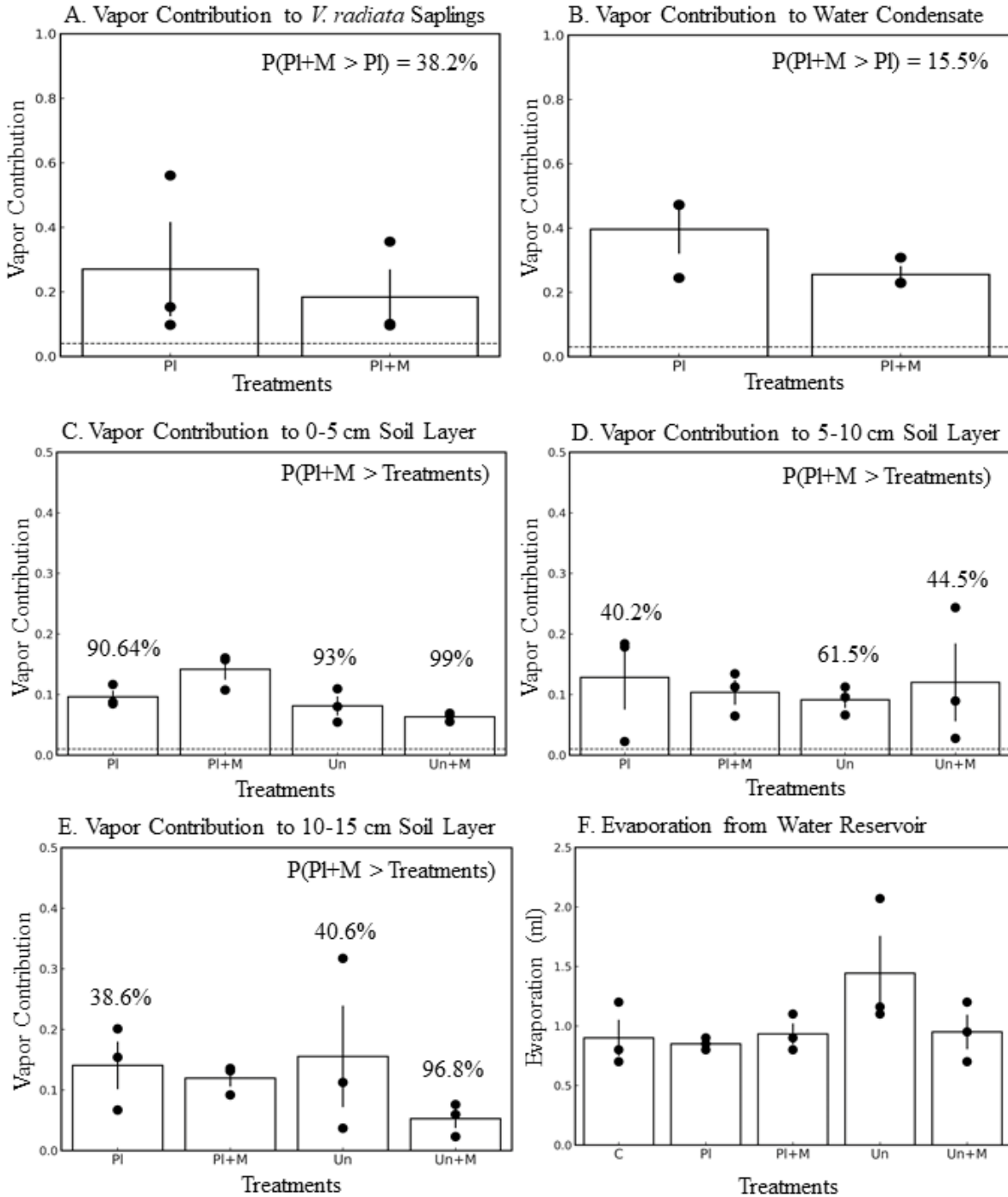
## E2.2 Data Analysis

Labeled water vapor contributions were estimated using a Bayesian mixing model (MixSIAR two-end framework) based on  $\delta^2H$  signatures of the labeled reservoir water (512.08‰) and control tap water (-53.38‰). All individual replicates from all treatments were included as mixtures. The model incorporated replicate variability and measurement uncertainty to generate posterior distributions of labeled water vapor contribution with 95% credible intervals for each sample group. Bayesian analysis based pairwise posterior probability detailed the overlap percentages while accounting for uncertainty. In addition, one sided Wilcoxon-Mann-Whitney-Test ( $p \leq 0.05$ ) was used to identify differences in vapor contribution to control and treatment column. Treatment effects on water vapor contribution were determined by Wilcoxon-Mann-Whitney-Test and Kruskal Wallis analysis. For statistical analysis R version 2024.12.0 Build 369 was used.

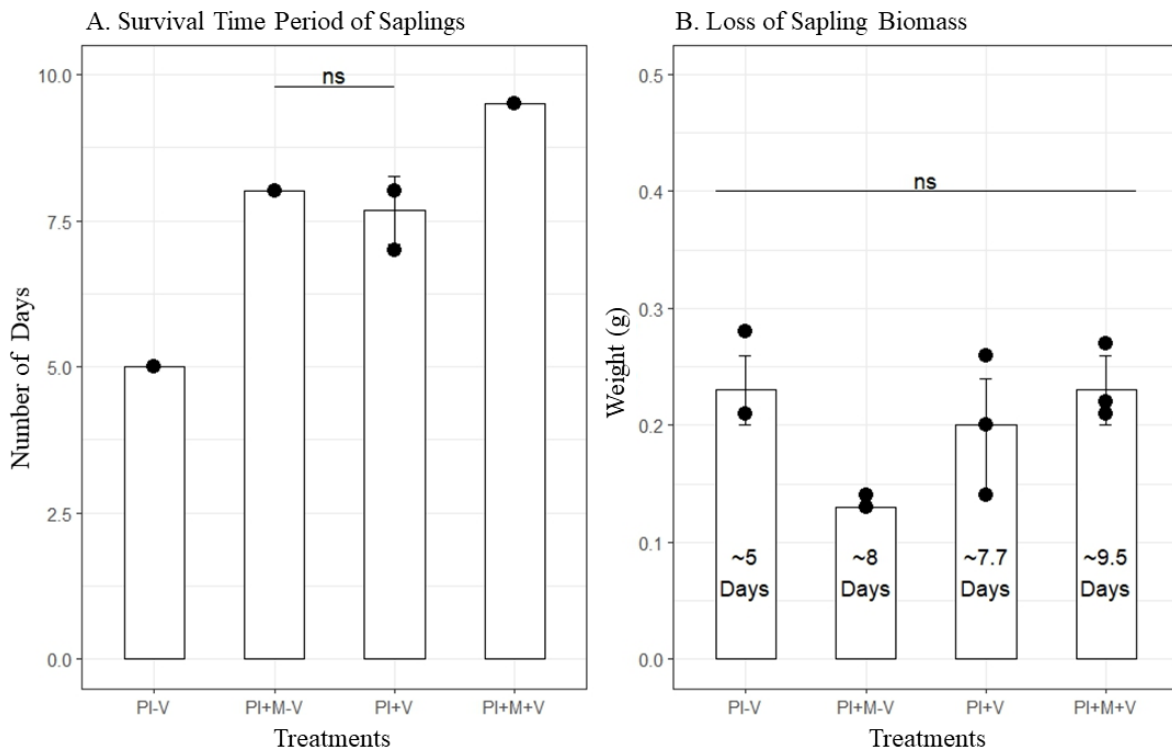
## E3 Results and Discussion

Bayesian posterior probability analysis revealed that mulched treatment (PI+M) had a 38.2% probability of having higher water vapor contribution to *V. radiata* saplings than unmulched treatment (PI) (Figure E2). Additionally, the water condensate collected from the inner headspace walls (originating from leaf respiration) of PI+M had a 15.5% probability of having higher vapor contribution than in PI. Correspondingly, saplings in the PI+M+V (planted, mulched and with water vapor source) survived for  $\sim 9.5$  days, which was significantly longer ( $p \leq 0.05$ ) than those in PI+V ( $\sim 7.7$  days), PI+M-V ( $\sim 8$  days) and PI-V ( $\sim 5$  days) (Figure E3A). Although the measured volume of vapor uptake was relatively low, the corresponding increase in plant survival suggests that water vapor played a disproportionately critical role in maintaining plant water balance. A Fick's law estimate gave a potential water vapor flux of  $\sim 0.29$  ml/day for the 55 cm soil column path, compared to the measured  $\sim 0.14$  ml/day, indicating the water uptake being consistent with water vapor driven flux. These results align with those of Mahdavi et al. (2020), who estimated a negligible vapor contribution to total soil moisture flux ( $\sim 1\%$ ) and Zheng et al. (2020), who found that even minimal vapor flux could support aboveground vegetation under extreme conditions. Moreover, the non-significant biomass loss across treatments despite different survival durations (Figure E3B) indicates that vapor uptake acted as a supplemental source that sustains basic metabolic functions

under drought (Kool et al., 2021), extending survival without promoting additional growth.



**Figure E2:** Vapor contribution to *V. radiata* saplings (A) and water vapor contribution to different soil column elements including; water condensate (B, from headspace section of the soil column), soil at different depths – 0–5 (C), 5–10 (D) and 10–15 cm (E). Posterior probabilities (PI+M > Treatment Groups) are represented with percentages. Graph F. details the total evaporation from the water reservoir. Treatments include PI (planted), PI+M (planted and mulched), Un (unplanted), Un+M (unplanted and mulched). Black dotted line represents mean vapor contribution of respective element under control. Bars are mean vapor contribution and points are data (n = 3).



**Figure E3:** A. Mean survival time period of *V. radiata* saplings. Treatments include PI-V (planted with no vapor source), PI+M-V (planted and mulched with no vapor source), PI+V (planted with a vapor source), PI+M+V (planted and mulched with a vapor source). Error bars represent standard error of the mean ( $n = 3$ ). ns shows the statistically non-significant differences among treatments. B. Mean biomass loss for *V. radiata* saplings over different number of days. The non-significant (ns) differences observed in biomass loss over significantly different time periods ( $p \leq 0.05$ ) display the biomass loss influenced by water vapor availability rather than external variability, validating the methodology.

While previous studies have primarily focused on vapor flux as a mechanism of soil water loss (Balugani et al., 2021; Lehmann et al., 2008; Or et al., 2013; Sakai et al., 2009; Zheng et al., 2020), the current study shifts the perspective toward the plant utilization of water vapor as a supplemental mechanism and its physiological relevance during drought. The findings provide evidence that *V. radiata* saplings can access and utilize water vapor from a spatially separated deep water reservoir, significantly contributing to their survival under drought conditions.

Several mechanisms may explain how water vapor supports plant water balance. One possible pathway is foliar water uptake, a mechanism whereby leaves directly absorb water vapor (Berry et al., 2019). However, this is unlikely to be a dominant factor in our experiment, as the constant outflow of air reduced water vapor concentration in the headspace section, limiting the potential for foliar uptake (Kool et al., 2021). Moreover, the consistent deuterium enrichment in both PI and PI+M treatments, despite mulch in PI+M presumably reducing

surface evaporation, suggest a non-foliar pathway. Another mechanism is the root-mediated uptake of water vapor. While roots can sense gradients in vapor concentration (Lind et al., 2021), there currently is no conclusive evidence that they can directly absorb vapor. Nevertheless, uptake of water vapor through soil media had been suggested to contribute to plant water dynamics (Allison et al., 1983; Vargas et al., 2020). Such water vapor-based contributions remain sparsely studied and are rarely incorporated into existing plant water uptake models, underscoring the relevance of this study in refining plant–soil–water interaction frameworks under drought.

In contrast, indirect uptake of water vapor when it condenses in soil is recognized (Beyer et al., 2020; Bhattacharya, 2021; Steudle, 2000). Given the absence of free liquid water in the system, the patterns are consistent with water vapor first condensing on soil particles and then being taken up, rather than direct vapor absorption by roots. The observed condensation at mulch further suggests that condensation may serve as an intermediary step in plant water acquisition. Such condensation driven uptake has been previously reported in controlled environments (Assouline et al., 2013; Deol et al., 2014) and is influenced by factors such as mulching (Ramos et al., 2024), diurnal temperature variations, presence of plants (Bhattacharya, 2021) and the rate of water vapor diffusion (Or et al., 2013). The day-night temperature fluctuations in our study could have induced condensation, while the application of mulch likely enhanced plant water availability (Wang et al., 2024). In this study, mulching significantly improved water retention and prolonged plant survival (Figure E2 and E3). By reducing surface evaporation (Demo et al., 2024), mulch altered the surface moisture conditions (Ramos et al., 2024) as detailed by the high probabilities in vapor contribution between mulched and un-mulched treatments at the 0-5 cm soil depth layer (Supplementary Material, Figure 3).

## **E4 Conclusion**

This study provides evidence that water vapor utilization from a spatially separated deep soil water reservoir can extend plant survival under drought conditions. The application of a mulch layer further reduced surface evaporation and improved plant available water. These findings highlight the potential role of water vapor in supporting plants during early vegetative stages when sensitivity to drought is high. Future research should aim to validate these results under field conditions across different plant species and environmental

settings, incorporating diurnal humidity fluctuations, nighttime dew formation and segregating evapotranspiration components to evaporation and transpiration to better understand water vapor flow and utilization efficiency in semi-arid regions. Field experiments considering environmental factors such as wind, temperature variability and high radiance could further clarify plant responses during critical crop establishment phases and help assess the potential complementary role of water vapor in supporting vegetation under drought prone sandy soil conditions. While vapor fluxes are limited, understanding their contribution may inform strategies to improve water vapor utilization for water-efficient agricultural practices.

### **Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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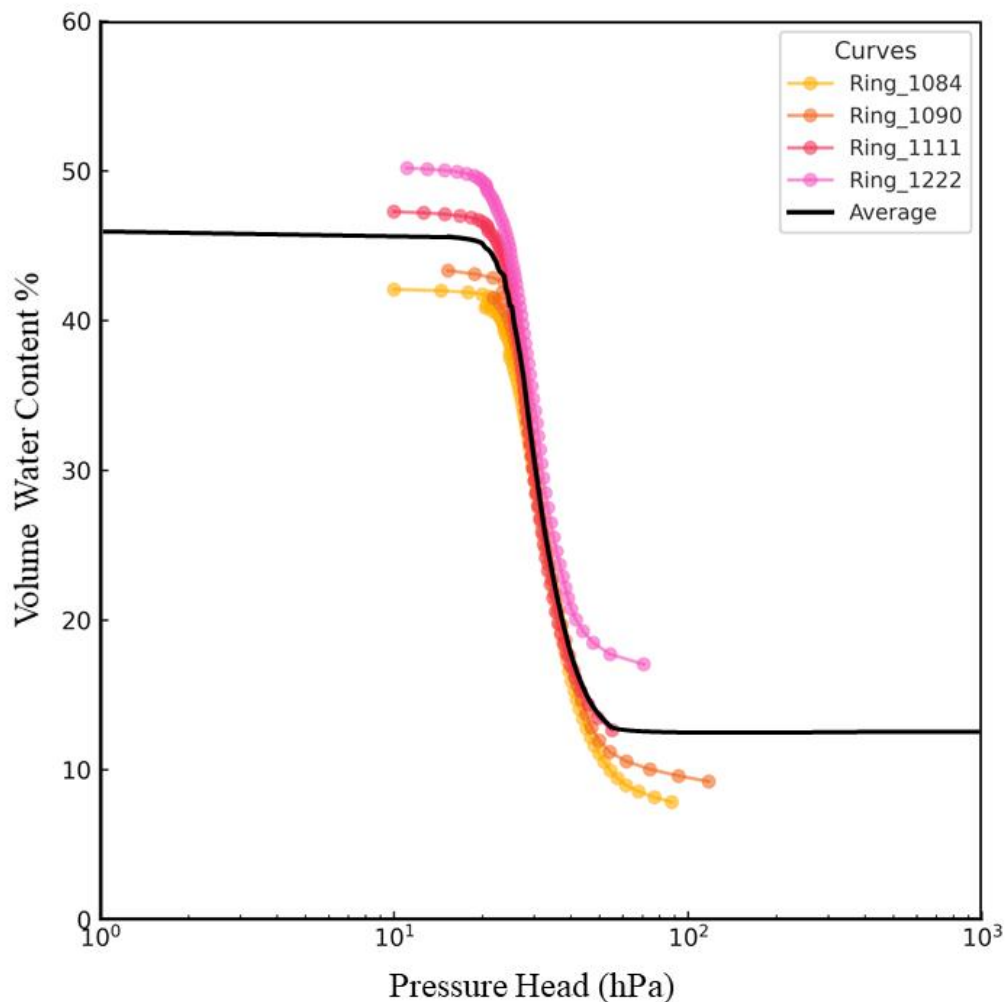
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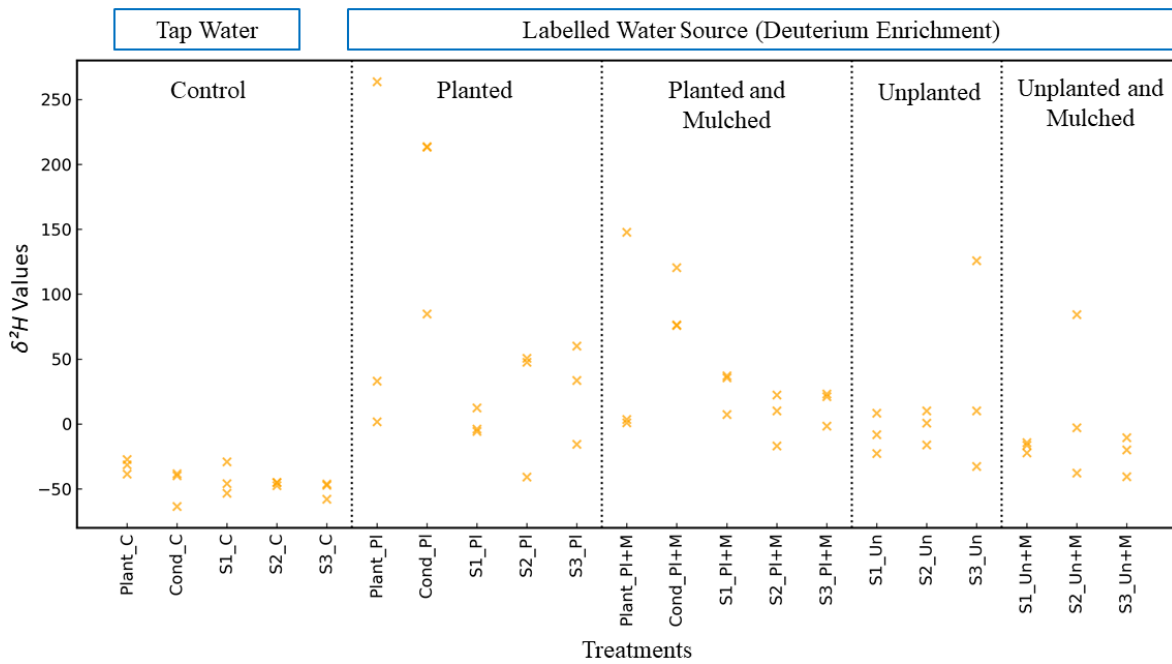
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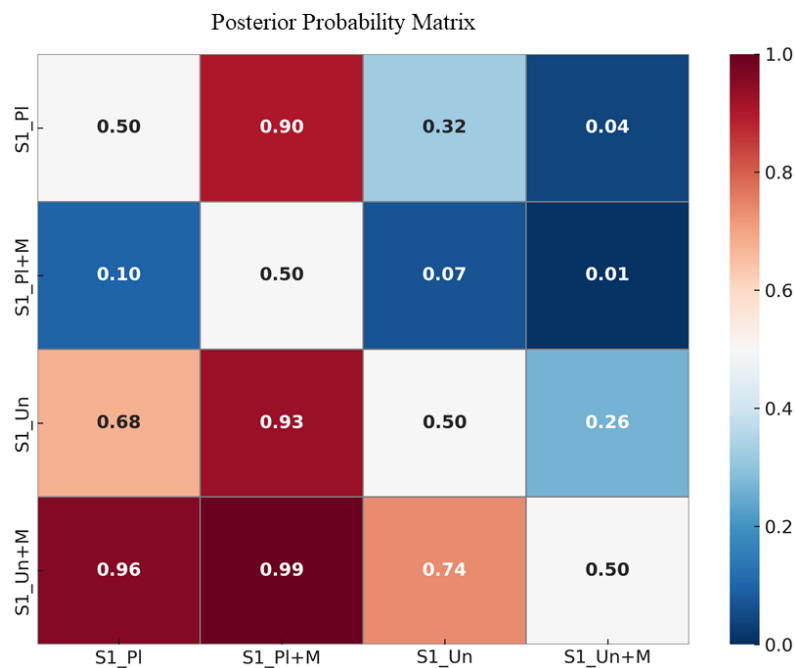
## E6 Supplementary Material



**Figure 1:** Soil water retention curves for sandy soil (four replicates - Ring\_1084, Ring\_1090, Ring\_1111 and Ring\_1222) fitted using the van Genuchten model.



**Figure 2:** Distribution of  $\delta^2H$  values across treatments under tap water (unlabeled) and deuterium-enriched (labeled) conditions. Treatments include; Control (C), Planted (PI), Planted and Mulched (PI+M), Unplanted (Un) and Unplanted + Mulched (Un+M). Samples include Plant (*V. radiata* saplings), Cond (water condensate from the head-space section), S1 (soil from depth 0-5 cm), S2 (soil from depth 5-10 cm) and S3 (soil from depth 10-15 cm).



**Figure 3:** Posterior probability matrix for soil depth 0-5 cm. Values are based on simulation-derived Bayesian estimates. Higher probabilities (closer to 1) indicate stronger evidence of high vapor contribution than the corresponding treatment.

Here, Plant\_C refers to the saplings under control treatment. Cond\_C is the water condensate signal from the headspace of soil column under control treatment. S1 is the soil sample from 0-5 cm depth. S2 is the soil sample from 5-10 cm depth and S3 refers to the soil sample from 10-15 cm depth.

## 1. Vapor Flux Estimation

A simple diffusion-based estimate of water vapor flux was performed using Fick's law:

$$J = D * (\Delta C / \Delta z)$$

Where,

J = vapor flux density (mol/m<sup>2</sup>/s)

D = diffusion coefficient of water vapor in porous media ( $\sim 1.13 \times 10^{-5}$  m<sup>2</sup>/s at 25–30 °C)

$\Delta C$  = concentration gradient of water vapor (mol/m<sup>3</sup>), that is the difference in vapor concentration (mol/m<sup>3</sup>) between reservoir and headspace

$\Delta z$  = distance between the water reservoir and headspace ( $\sim 0.55$  m)

Assumptions and values:

- Bulk density = 1.19 g/cm<sup>3</sup>
- Estimated porosity =  $\sim 0.55$
- Tortuosity correction factor (Millington-Quirk) = 0.45
- Diffusion coefficient in free air =  $2.5 \times 10^{-5}$  m<sup>2</sup>/s
- Diffusion coefficient in porous media =  $1.13 \times 10^{-5}$  m<sup>2</sup>/s
- Reservoir relative humidity =  $\sim 100$  %
- Headspace relative humidity =  $\sim 10$  %
- Temperature = 25–30 °C (assumed 298 K)
- Saturation vapor pressure at 25–30 °C =  $\sim 3.2$  kPa
- Cross-sectional area of the column with 10 cm diameter (A) = 0.00785 m<sup>2</sup>
- Steady-state diffusion and uniform gradient assumed

First, the concentration gradient of water vapor ( $\Delta C$ ) was calculated using the ideal gas law:

$$C = e / RT$$

$$\Delta C = (e_{\text{reservoir}} - e_{\text{headspace}}) / (R T)$$

Where,

e = vapor pressure (Pa)

R = universal gas constant (8.314 J/mol·K)

T = absolute temperature (287 K at 25–30°C)

If the reservoir is at 100% relative humidity and headspace is at  $\sim 10$ % relative humidity (dry air), then, the conversion of relative humidity to actual vapor pressure is defined as:

$$e = RH \times e_s$$

Where:

$e$  = actual vapor pressure (Pa)

RH = relative humidity (fraction, not %)

$e_s$  = saturation vapor pressure at that temperature

For the reservoir:

$$\text{RH} = 100\% = 1.0$$

$$e_{\text{reservoir}} = 1.0 \times 3.2 \text{ kPa} = 3.2 \text{ kPa} = 3200 \text{ Pa}$$

For the headspace:

$$\text{RH} = 10\% = 0.10$$

$$e_{\text{headspace}} = 0.10 \times 3.2 \text{ kPa} = 0.32 \text{ kPa} = 320 \text{ Pa}$$

Resulting in the concentration gradient of water vapor:

$$\Delta C = (3200 - 320) / (8.314 \times 298) = \sim 1.16 \text{ mol/m}^3$$

Given these estimations we can now calculate the flux (J):

$$J = D * (\Delta C / \Delta z)$$

$$J = (1.13 \times 10^{-5}) \times (1.16 / 0.55) = \sim 2.38 \times 10^{-5} \text{ mol/m}^2/\text{s}$$

We further convert flux to total water per day per column:

We have,

$$J = 2.38 \times 10^{-5} \text{ mol/m}^2/\text{s}$$

$$\text{Column diameter} = 10 \text{ cm} = 0.10 \text{ m}$$

$$\text{Cross-sectional area (A)} = \pi r^2 = \pi (0.05)^2 = 0.00785 \text{ m}^2$$

Calculate moles per second for the column:

$$\text{Flux per second} = J \times A = (2.38 \times 10^{-5}) \times 0.00785 = 1.87 \times 10^{-7} \text{ mol/s}$$

Conversion to moles per day:

$$\text{Flux per day} = 1.87 \times 10^{-7} \times 86400 = 0.0161 \text{ mol/day}$$

Conversion to ml per day (1 mol H<sub>2</sub>O = ~18ml):

$$0.0161 \times 18 = \sim 0.29 \text{ ml/day}$$

Estimated water vapor flux = ~ 0.29 ml/day for the ~55 cm vapor path with 10% relative humidity in the headspace.

## 2. Vapor Pressure Gradient Estimation

To estimate the vapor pressure gradient maintained in the soil column between the water reservoir and the headspace, we assume:

- Temperature in the chamber =  $\sim 25\text{ }^{\circ}\text{C}$  (298 K)
- Reservoir relative humidity = 100 % = 1.0
- Headspace relative humidity = 10% = 0.1
- Vertical distance between reservoir and headspace ( $\Delta z$ ) = 55 cm = 0.55 m
- Saturation vapor pressure of water at  $25\text{ }^{\circ}\text{C}$  ( $e_s$ )  $\approx 3.2\text{ kPa}$

Based on our calculation, vapor pressures were:

$$e_{\text{reservoir}} = \text{RH}_{\text{reservoir}} \times e_s = 1.0 \times 3.2\text{ kPa} = 3.2\text{ kPa} = 3200\text{ Pa}$$

$$e_{\text{headspace}} = \text{RH}_{\text{headspace}} \times e_s = 0.10 \times 3.2\text{ kPa} = 0.32\text{ kPa} = 320\text{ Pa}$$

Vapor pressure gradient (VPG) was:

$$\Delta e = e_{\text{reservoir}} - e_{\text{headspace}} = 3200 - 320 = 2880\text{ Pa}$$

$$\text{VPG} = \Delta e / \Delta z = 2880\text{ Pa} / 0.55\text{ m} = 5236\text{ Pa/m} = \sim 5.2\text{ kPa/m}$$

The estimated vapor pressure gradient maintained in the system was approximately 5.2 kPa/m, based on 100 % RH in the reservoir and 10 % RH in the headspace at  $25\text{ }^{\circ}\text{C}$ .

**Table 1:** Experiment 1

<b>Sample</b>	<b>d2H Values</b>	<b>Vapor Contribution</b>	<b>Mean Vapor Contribution</b>	<b>Treatment</b>	<b>Evaporation (ml)</b>
Plant_C	-38.58	0.0261341061	0.04	C	0.7
Plant_C	-31.24	0.0391559644		C	0.8
Plant_C	-27.16	0.0463753850		C	1.2
Cond_C	-38.17	0.0268883289	0.03	PI	0.9
Cond_C	-39.74	0.0241275416		PI	0.85
Cond_C	-63.54	0.0000000000		PI	0.8
S1_C	-29.01	0.0430647444	0.01	PI+M	0.8
S1_C	-45.95	0.0131349718		PI+M	0.9
S1_C	-53.29	0.0010774457		PI+M	1.1
S2_C	-45.03	0.0147682748	0.01	Un	1.1
S2_C	-47.46	0.0105366292		Un	2.07
S2_C	-44.73	0.0152922819		Un	1.16
S3_C	-57.81	0.0000005660	0.00	Un+M	0.7
S3_C	-47.11	0.0111434201		Un+M	0.95
S3_C	-46.09	0.0129504664		Un+M	1.2
Plant_PI	263.65	0.5606463370	0.20		
Plant_PI	1.86	0.0976698972			
Plant_PI	33.18	0.1530741133			
Cond_PI	213.16	0.4713923517	0.38		
Cond_PI	213.67	0.4722899857			
Cond_PI	84.90	0.2445030127			
S1_PI	-3.86	0.0876000001	0.10		
S1_PI	-5.52	0.0846555789			
S1_PI	12.51	0.1165124491			
S2_PI	-40.74	0.0223650600	0.09		
S2_PI	47.55	0.1784825000			
S2_PI	50.57	0.1838145212			
S3_PI	-15.56	0.0668711823	0.13		
S3_PI	33.65	0.1539189663			
S3_PI	60.23	0.2009219572			
Plant_PI+M	3.55	0.1007130408	0.15		
Plant_PI+M	0.96	0.0960564803			
Plant_PI+M	147.71	0.3556107870			
Cond_PI+M	120.55	0.3075794598	0.25		
Cond_PI+M	76.48	0.2296713712			
Cond_PI+M	75.97	0.2287400690			
S1_PI+M	37.27	0.1603426914	0.14		
S1_PI+M	7.37	0.1074280890			
S1_PI+M	35.62	0.1573992970			
S2_PI+M	-16.93	0.0645296061	0.10		
S2_PI+M	10.23	0.1124774568			
S2_PI+M	22.51	0.1342298543			
S3_PI+M	-1.51	0.0917646662	0.12		
S3_PI+M	21.01	0.1315849721			

Sample	d2H Values	Vapor Contribution	Mean Vapor Contribution	Treatment	Evaporation (ml)
S3_PI+M	23.24	0.1354917168			
S1_Un	-22.60	0.0544273077	0.08		
S1_Un	-8.07	0.0801347213			
S1_Un	8.51	0.1094294640			
S2_Un	-16.01	0.0661195352	0.09		
S2_Un	0.65	0.0956078542			
S2_Un	10.16	0.1123298317			
S3_Un	-32.54	0.0368355182	0.11		
S3_Un	125.94	0.3171269775			
S3_Un	10.18	0.1123864634			
S1_Un+M	-22.15	0.0552117113	0.06		
S1_Un+M	-14.38	0.0689650825			
S1_Un+M	-16.30	0.0655796641			
S2_Un+M	-37.78	0.0276002696	0.08		
S2_Un+M	84.29	0.2434691070			
S2_Un+M	-2.86	0.0893464435			
S3_Un+M	-40.41	0.0229277605	0.05		
S3_Un+M	-19.78	0.0594238465			
S3_Un+M	-10.46	0.0758764872			

Here, \_C: Control Treatment, \_PI: Planted Treatment, \_PI+M: Planted and Mulched Treatment, \_Un: Unplanted Treatment, \_Un+M: Unplanted and Mulched Treatment, Plant: *Vigna radiata* saplings, Cond: Condensed Water Sample, S1: Sample from soil depth 0-5 cm, S2: Sample from soil depth 5-10 cm, S3: Sample from soil depth 10-15 cm. Evaporation recorded from the bottom water reservoir.

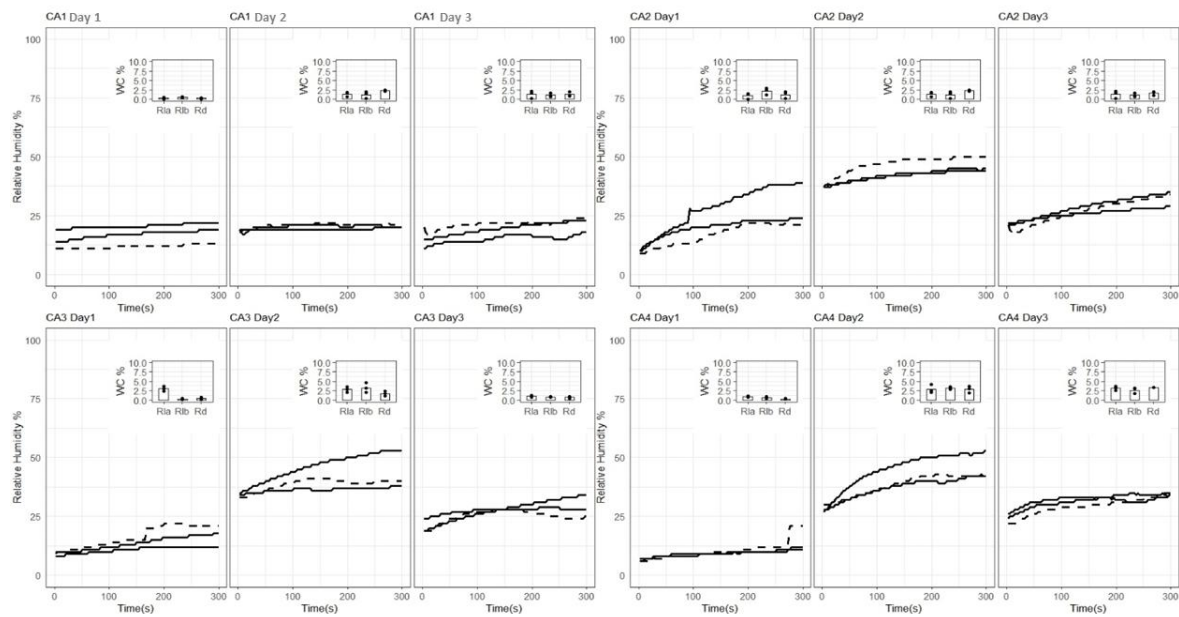
**Table 2:** Experiment 2

Treatments	Survived Days	Mean	SD
PI-V	5	5	0
PI-V	5		
PI-V	5		
PI+M-V	8	8	0
PI+M-V	8		
PI+M-V	8		
PI+V	7	7.67	0.58
PI+V	8		
PI+V	8		
PI+M+V	9.5	9.5	0
PI+M+V	9.5		
PI+M+V	9.5		

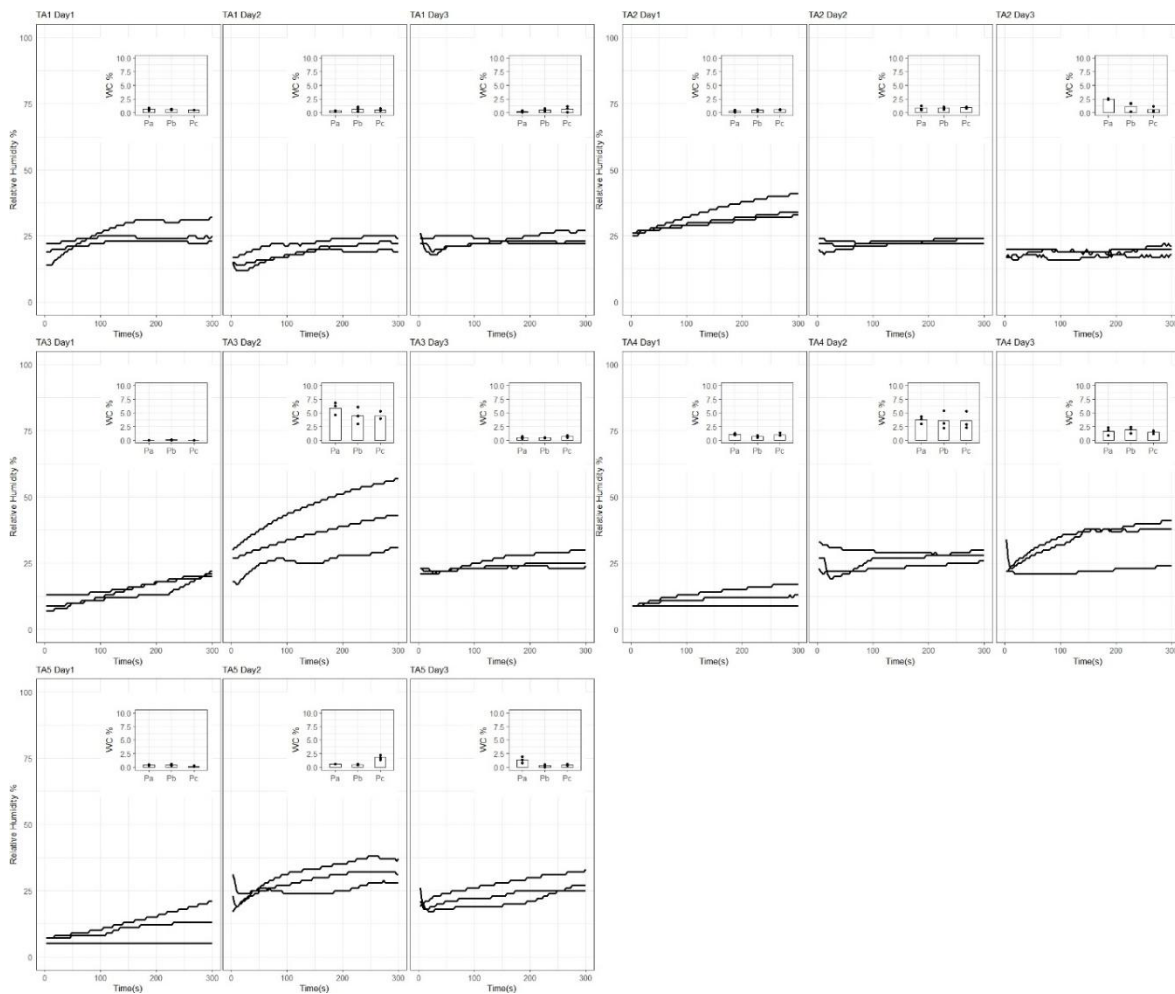
Here, PI: Planted Treatment, PI+M: Planted and Mulched Treatment, -V: Without Vapor Source, +V: With Vapor Source

## Appendix

### Study A: Investigating soil water dynamics to improve agriculture: Namibian land-use systems under drought

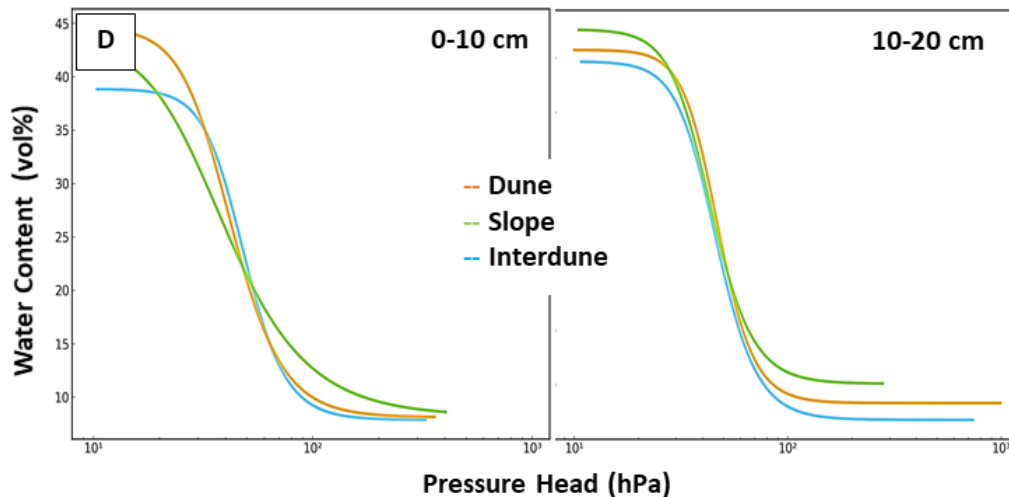


**Figure 1:** Relative humidity trends recorded during closed chamber measurements for conservation agricultural sites (CA1, CA2, CA3, CA4). WC% is soil moisture content at 0-10 cm soil depth.



**Figure 2:** Relative humidity trends recorded during closed chamber measurements for traditional agricultural sites (TA1, TA2, TA3, TA4, TA5). WC% is soil moisture content at 0-10 cm soil depth.

### Study B: Soil water dynamics along the Kalahari dune transects in northern Namibia



**Figure 1:** Results detailing retention curves for different dune topographic positions.

**Table 1:** Soil properties along the soil profiles of different topographic positions of dunes.

TP	Horizon	Depth (cm)	pH (H <sub>2</sub> O)	Sand (%)	BD (g/cm <sup>3</sup> )
Dune	1	0 - 10	5.76 ± 0.06	96.30 ± 0.22	1.55 ± 0.02
Dune	2	10 - 20	5.69 ± 0.16	95.82 ± 0.42	1.58 ± 0.01
Dune	3	20 - 60	5.70 ± 0.17	95.51 ± 0.19	1.56 ± 0.01
Dune	4	60 - 100	5.52 ± 0.07	95.03 ± 0.31	1.57 ± 0.01
Slope	1	0 - 10	5.48 ± 0.23	95.88 ± 0.88	1.56 ± 0.01
Slope	2	10 - 20	5.46 ± 0.15	95.38 ± 0.46	1.60 ± 0.01
Slope	3	20 - 60	5.39 ± 0.13	95.93 ± 1.20	1.60 ± 0.01
Slope	4	60 - 100	5.40 ± 0.04	94.11 ± 0.43	1.60 ± 0.01
Interdune	1	0 - 10	5.94 ± 0.39	95.26 ± 2.26	1.58 ± 0.02
Interdune	2	10 - 20	5.86 ± 0.44	94.39 ± 2.45	1.55 ± 0.05
Interdune	3	20 - 60	5.74 ± 0.45	94.46 ± 1.88	1.57 ± 0.05
Interdune	4	60 - 100	5.70 ± 0.40	93.30 ± 2.78	1.57 ± 0.04

TP	Horizon	Porosity (vol%)	FC (vol%)	C (%)	C/N
Dune	1	41.50 ± 0.78	14.27 ± 4.24	0.22 ± 0.06	9.32 ± 1.55
Dune	2	40.72 ± 0.29	18.83 ± 0.65	0.12 ± 0.02	7.85 ± 1.21
Dune	3	41.29 ± 0.47	18.75 ± 3.95	0.09 ± 0.01	6.20 ± 1.24
Dune	4	41.06 ± 0.42	18.81 ± 2.05	0.07 ± 0.01	6.14 ± 0.53
Slope	1	41.26 ± 0.59	16.09 ± 0.99	0.21 ± 0.04	8.18 ± 0.98
Slope	2	39.77 ± 0.55	11.21 ± 3.01	0.15 ± 0.02	7.03 ± 1.02
Slope	3	39.92 ± 0.30	12.35 ± 2.82	0.11 ± 0.0	6.75 ± 0.13
Slope	4	39.93 ± 0.39	11.17 ± 1.87	0.07 ± 0.01	5.00 ± 1.19
Interdune	1	40.26 ± 0.58	14.20 ± 3.39	0.24 ± 0.04	10.31 ± 0.18
Interdune	2	41.19 ± 1.74	16.82 ± 0.89	0.18 ± 0.04	9.05 ± 1.27
Interdune	3	40.72 ± 1.83	15.57 ± 0.36	0.11 ± 0.02	7.61 ± 1.06
Interdune	4	40.76 ± 1.44	18.91 ± 1.55	0.09 ± 0.01	6.25 ± 0.44

Here, TP: Topographic Position, BD: Bulk Density, FC: Field Capacity, C: Soil Organic Carbon, C/N: Soil Organic Carbon by Total Nitrogen Ratio

## Study D: Cowpea growth response to mulching and inoculation modifying soil water balance under simulated drought

**Table 1:** Chemical composition of wood chips and wheat straw materials used as mulch in greenhouse pot experiment.

Mulch material	C (%)	N (%)	C/N
Wood chips	44.13	0.72	61.30
Wheat straw	43.14	0.44	97.17

Here, C: Carbon, N: Nitrogen, C/N: Carbon to Nitrogen Ratio



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