Aspects of the water use of *Cannabis sativa L.* under dryland cultivation in the Eastern Cape

by

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Declaration

I, Kamva Trevor Songo Zenani, hereby submit this thesis in accordance with Rhodes University's plagiarism policy. I affirm that all content within this document is the result of my own original work, and any external contributions are duly acknowledged. To the best of my knowledge, this thesis has not been previously submitted in its current form for any degree elsewhere.

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Abstract

Cannabis spp is one of the oldest cultivated plants, with its origin in Asia. It has two species, namely *C. indica* and *C. sativa*. This research focuses on *C. sativa*, which is widely cultivated locally and globally. *C. sativa* has a wide range of uses, including industrial, medicinal, religious, and recreational. This study will be focusing on the water use of medicinal and recreational *C. sativa* grown under dryland conditions. In recent years, there has been a growing interest in increasing its cultivation, but there are reports of it having high water usage. The global interest has led many governments to review the laws governing this plant as it is a controlled substance in many countries.

Due to its legal status, there is a dearth of knowledge about its growth and water use. It is against this backdrop that the Water Research Commission (WRC) commissioned this study into the water use of this plant. This will provide evidence-based support for the issuing of water use licenses by the Department of Water and Sanitation. The Eastern Cape and KwaZulu Natal have many small-scale legacy farmers who have been growing *C. sativa* illegally for decades. The findings of this research will seek to fill some of these knowledge gaps and assist legacy farmers in the cultivation of this plant.

This research had four approaches, which include 1) planting the crop in a dryland location that will mimic the conditions experienced by legacy growers, 2) the collection of plant biophysical variables in the study site in order to gain a better understanding of the plant's health, growth, progress, and to use these variables to parameterize a mechanistic eco-physiological model, 3) the installing of a large aperture scintillometer (LAS) together with a micro-meteorological station to measure the evapotranspiration (ET) and meteorological parameters over a crop cycle, 4) to use MEDRUSH evapotranspiration model to predict the ET and compare these results against that of the LAS.

The results show that water provision had a significant impact on plant biophysical variables and water use. The plants received 154 mm (2 mm day^{-1}) of rain during the crop cycle. The large aperture scintillometer recorded a total ET of 126.8 mm (1.76 mm day^{-1}) during the same period. The MEDRUSH model (2.5 mm day^{-1}) overestimated the LAS ET (1.79 mm day^{-1}), and the results from the daily ET revealed that *C. sativa* had higher daily ET when compared to the local grass *Eragrostis plana.* These results confirm that at this location in the Eastern Cape*, C. sativa* requires regular irrigation during the growing season to grow and secure a crop.

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Contents

List of figures

List of tables

List of acronyms

AET	Actual Evapotranspiration
CB1	Cannabinoid receptor 1
CB2	Cannabinoid receptor 2
CBD	Cannabidiol
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CMA	Catchment Management Agency
CO_2	Carbon dioxide
DAFF	Department of Agriculture, Fisheries and Forestry
DEA	Department of Environmental Affairs
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
ET	Evapotranspiration
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAO	Food and Agriculture Organisation
G	Soil heat flux
g_s	Stomatal conductance
LAI	Leaf Area Index
LAS	Large Aperture Scintillometer
LTAS	Long Term Adaptation Scenario
NOAA	United States National Oceanic and Atmospheric Administration
O_2	Oxygen
PET	Potential ET
RET	Reference Evapotranspiration
R_n	Net radiation
SAHO	South African History Online
SWC	Volumetric soil water content
SONA	State of the Nation Address
THC	Tetrahydrocannabinol
USGS	United States Geological Survey
WMO	World Meteorological Organization
WRC	Water Research Commission

Preamble

Cannabis sativa (*c. sativa*) is one of the oldest cultivated plants in the world, and because of its long cultivation history, it has been viewed differently by many societies and groups of people around the globe (Abel, 1980). One of these groups of people are legacy farmers, who can be defined as farmers that have been cultivating *C. sativa* for a minimum of 20 years (Duncan, 2022). These legacy farmers can be found across the globe for example, the Humboldt, Sonoma, Trinity and Mendocino counties in the United States of America have a number of these legacy farmers (Duncan, 2022). South Africa has these legacy farmers as well and they are primarily found in remote rural areas of the Eastern Cape and KwaZulu Natal Provinces (Hojgaard, 2021). They usually cultivate *C. sativa* in small garden plots under dryland conditions and in some cases the *C. sativa* is planted with *Zea mays* (maize) and other vegetables in order hide it from authorities (Hojgaard, 2021). These farmers in the Eastern Cape are found predominantly in Mpondoland region (Duvall 2019b; Kepe 2003). This area is remote and is characterized by deep gorges and rolling ever green hills, and is poorly serviced by roads and communication infra-structure. This remoteness is one of the key reasons why the area is a top producer of *C. sativa* in South Africa. The remoteness of the region is a key reason for it being a top producer, as it affords the farmers the opportunity to evade law enforcement agents since *C. sativa* is still a controlled substance. Additionally, remoteness provides various benefits, such as increased privacy, reduced interference, and better control over cultivation conditions. The landscape is also a major disadvantage because it hinders development due to the high cost associated with developing infrastructure such as roads, bridges, rail and ports in the area and it makes it hard for commercial agriculture to take place as well. All these factors contribute to the extreme poverty in the area. According to Stats South Africa (2019) the Eastern Cape Province is the second poorest province, with a very high unemployment rate (40%). Government social grants, remittances and subsistence farming are the main source of income and often, this is not enough to sustain families (Winchester et al., 2021).

It is against this backdrop that the people of this region adopted the practice of cultivating and selling *C. sativa. Cannabis sativa* has the ability to grow in harsh environments with minimal input and therefore it became the perfect source of income in poor remote areas (Hojgaard, 2021). This phenomenon can be observed in other poor and remote areas of the world like the highlands of the Kingdom of Lesotho where *C. sativa* has been cultivated for decades (Hojgaard, 2021). This phenomenon can be observed in other poor and remote regions of the world such as the dense tropical rainforests of the Amazon in Colombia where the coca plant is cultivated, and the mountains of Afghanistan where opium is grown (Goodhand, 2005; Leggett, 2006). Bloomer (2009) argues that

C. sativa cultivation in poverty stricken and remote areas like the aforementioned should not be viewed as criminal opportunism but as a coping strategy against poverty.

The Government of South Africa for many years has been trying to alleviate poverty in rural areas by creating a sustainable economy (Bowman & Lehmann-Grube, 2023). The cultivation of *C. sativa* has been identified as one of the ways this poverty alleviation could be achieved (Eastern Cape Rural Development Agency, 2020). It is against this backdrop that the Water Research Commission (WRC) commissioned a study into the water use of *C. sativa* since there was a dearth in knowledge about its water use. The study focuses on legacy farmers of the Eastern Cape and tries to mimic and simulate the conditions these farmers work under. The legacy farmers cultivate a traditional landrace as opposed to cultivars (Hojgaard, 2021).

In this study a limited number of agricultural inputs were used, in order to mimic the conditions these farmers operate under. In order to assess plant-growth this study focused on water-related measurements. These measurements are important because South Africa is semi-arid (Department of Environment Affairs, 2013). It is faced with climate change that has the potential to exacerbate the water problem in the country by causing more erratic rainfall patterns (Department of Environment Affairs, 2013). There is also a knowledge gap in the water use of C. sativa (Chapagain and Tickner, 2012; Department of Environment Affairs, 2013). It is therefore imperative that water use is regulated because it is a scarce and limited resource. The National Water Act of 1998 states that all water uses must be authorized by the Department of Water and Sanitation or a Catchment Management Agency (CMA) except water used for human consumption. Therefore, in order to cultivate *C. sativa*, it is imperative that it's water use is known. This research will aid greatly in the filling of the knowledge gap about the water use of *C. sativa* and could in the near future aid the Department of Water and Sanitation make informed decision about issuing of water use licenses.

This research was not a conventional agricultural trial, as the instrumentation used to measure water use requires a fetch of more than 150 m, with the crop growing directly beneath the beam of the instrument. A Large Aperture Scintillometer, which measures the water fluxes immediately above the crop, was installed in a remote location outside Makhanda and evapotranspiration data from the field was obtained. The results obtained from the LAS were then used to train a process-based evapotranspiration model, MEDRUSH. Stomatal conductance (measured using a leaf porometer) was recorded regularly through the crop growing cycle, and was used to parameterize the MEDRUSH model. The *C. sativa* was cultivated in an abandoned agricultural field, this is important to highlight because most of the agricultural land used by legacy farmers was previously abandoned (Andrew and Fox, 2010). Andrew et al., (2003) estimates that land abandoned range from 20–100 %, with the

highest levels of abandonment (100 per cent) being recorded in parts of the Ciskei. Many of the legacy farmers are from former homelands such as the Transkei, Ciskei and KwaZulu, where most of this land abandonment is rife (Andrew and Fox, 2004). It was therefore important that a very similar landscape was selected in order to mimic these conditions. The crops growing in the field enabled simulated the dryland environmental conditions faced by the legacy farmers and gave insight into the water use of this plant when grown in these areas with limited input (irrigation and fertilizer).

The outline of the thesis is as follows:

- Chapter 1 Introduction
- Chapter 2 Theoretical Background and literature review
- Chapter 3 Methodology
- Chapter 5 Results
- Chapter 6 Discussion
- Chapter 7 Conclusion

Chapter 1. Introduction

1.1. Background of Cannabis sativa origins and history

1.1.1 Origins of *Cannabis sativa*

Cannabis sativa L. is a herbaceous plant belonging to the family Cannabaceae (Wimalasiri et al., 2021) and is estimated to have been growing on Earth for at least 55 million years (Duvall, 2014). It originated in the Eocene geological period (Duvall, 2014; Andre et al., 2016). Evidence suggests that it has its roots in the present-day continent of Asia (Andre et al., 2016), with *C. sativa* now found in Central Asia and *C. indica* found in the Indian subcontinent (Duvall, 2014). The divergence of these two species was due to a number of biophysical changes that occurred over a period of time (Warf, 2014). One significant change occurred with the collision of the Indian subcontinent and Laurasia, leading to the formation of the Himalaya Mountain range. This event, known as the Himalaya orogeny, disrupted the moisture flow from the ocean into Central Asia (Nath, 1961; Klumper and Thacker, 2019). Climate change was thus a leading cause of the divergence between the two species. *Cannabis sativa* is further divided into two categories based on its use and tetrahydrocannabinol (THC) content; these are hemp and marijuana. Tetrahydrocannabinol is a psychoactive compound found in the *C. sativa* plant (Malabadi et al., 2023). It is one of over 100 cannabinoids present in *C. sativa*, and it is responsible for the plant's psychoactive effects (Wimalasiri et al., 2021; Malabadi et al., 2023). Tetrahydrocannabinol interacts with the endocannabinoid system in the human body, particularly with CB1 receptors in the brain and central nervous system (Malabadi et al., 2023). Medicinal *C. sativa* or marijuana (recreational drug) has a higher THC content when compared to the industrial hemp (Wimalasiri et al., 2021). Medicinal *C. sativa* has a THC content ranging from 0.3 to 38% of dry weight while the THC of industrial hemp ranges from 0 to 0.3% (Malabadi et al., 2023). Another major difference is how the two types are cultivated and the purpose of their cultivation. Industrial hemp is typically cultivated in large fields with closely spaced plantings to optimize the production of fibre or seeds, with a strong focus on achieving maximum quantity and efficiency (Crippa et al., 2012; Malabadi et al., 2023b). In contrast medicinal *C. sativa* is cultivated with a focus on the specific needs of the plant to maximize the production of cannabinoids efficiently (Crippa et al., 2012; Malabadi et al., 2023b). This may involve more controlled environments like tunnels, selective breeding, and specific cultivation techniques (Malabadi et al., 2023a). Indoor cultivation of *C. sativa* usually requires a substantial amount of water compared to outdoor cultivation (Bustic and Brenner, 2016; Dillis et al., 2020). These represent significant differences between these two varieties of *C. sativa*, though there are additional differences beyond these mentioned points.

Humans came into contact with the plant about 30 000 years ago on the Asian steppe in present day Mongolia and Southern Siberia after humans left Africa (Warf, 2014). Abel (1980) suggests that cultivation of *C. sativa* started in China about 12 000 years ago and farmers produced hempseed fibre. They used it to make ropes, sails for ships and clothing. It was used for its psychoactive properties i.e., substances that affect the mind, as well as for religious and spiritual purposes. *Cannabis sativa* is one of the oldest cultivated crops on Earth (Abel, 1980). It has spread to almost every corner of the globe (Warf, 2014). It spread from Central Asia towards the Middle East then to Europe, Africa and later on it was spread to the Americas by European settlers (Warf, 2014). It was in the Indian subcontinent where *C. sativa* saw widespread use especially in religious and spiritual settings (Klumper and Thacker, 2019). This was after the decline of its use in East Asia (China, Korea and Japan) due to the rise in Confucianism (Li, 1974). Abel (1980) suggests that this decline was due to the moral stance taken by the proponents of Confucianism, who argued against the use of this plant due to its perceived adverse consequences in communities. *Cannabis sativa* was brought to the Indian subcontinent by Nomadic peoples and merchants who crisscrossed the famous silk road selling and buying merchandise (Zuardi, 2006). It was in India where evidence points to the widespread use of *C. sativa* for religious and medicinal purposes.

1.1.2 Religion and *C. sativa* in various region of the world

India has a long history of spiritual and religious use of *C. sativa* (Bennet et al., 1995). It was believed that *C. sativa* had links with the spiritual realms and was associated with a number of deities, chief amongst them was Ganja (thought to be derived from the Ganges River) (Bennet et al., 1995). It was widely used by Zoroastrianism priests, who believed it bridged the gap between the metaphysical and spiritual world (Eliade, 1987). Scythian shamans used *C. sativa* in their purification ritual ceremonies (Benet, 1975). It is believed that it was the Scythes and Thracians who first introduced the plant to Eastern Europe from the Asian Steppes (Clarke and Merlin, 2013). In Eastern Europe, the plant did not see widespread use in religious settings, but hemp has been found in some traditional dishes such as soups (Benet, 1975). Western Europe followed the same trend as Eastern Europe as the plant was not widely used in religious practices; in fact, the Catholic Church prohibited the use of *C. sativa*, and it was mostly used in the medical realm (Booth, 2003). In the Middle East, *C. sativa* has been in use for millennia and has been found in various burial sites in Egypt, which would suggest that it was used to some extent for religious purposes (Abel, 1980). In the Arab world, *C. sativa,* which was referred to as Hashish, was first used by the adherents of Sufism, a branch of Islam, to bring them closer to God (Abel, 1980). *Cannabis sativa* eventually made its way into Africa through contact and trade between North and East Africa (Van der Merwe, 1975). Van der Merwe (1975) further suggests that the plant was used in Ethiopia, and it spread to the interior of Africa and was used by the Bantu-speaking

peoples of Central and Southern Africa (Warf,2014). There is no concrete evidence to suggest that *C. sativa* was used for religious purposes in many parts of Central and Southern Africa although in some parts of South Africa, in particular Eastern Cape Province, a few communities use it during their cultural ceremonies when communicating with ancestors, but it is not widespread. Warf (2014) suggests that *C. sativa* was only introduced in the 20th century, and thus, there are no religious uses associated with the plant in the region owing to its late arrival.

In the Americas, *C. sativa* arrived much later than the other continents due to the continent's isolation from the rest of the world (Partridge, 1975). It was brought by European settlers and African slaves. Angolan Slaves in Brazil and the Indigenous people of Mexico used *C. sativa* as part of their religious practices. The most famous religious use of *C. sativa* is found in the Rastafarian religion of the Caribbean Island of Jamaica (Pretorius, 2006). It was made famous by world-renowned reggae musicians like Robert Nesta Marley (Bob Marley), Peter Tosh, etc. In the Rastafarian religion *C. sativa* is used as a sacrament (Pretorius, 2006). The use of *C. sativa* has spread to all corners of the world but its use in religious settings has seen a decline and it is mostly used for recreational and medicinal purposes.

1.1.3 History of Medical use

Cannabis sativa has a wide range of uses, ranging from recreational to medicinal use (Warf, 2014). The latter is poorly understood due to the legal status of this plant in many modern societies (Bridgeman and Abazia, 2017). Despite this lack of research, recent studies point to some positive results when it comes to the medicinal properties of *C. sativa* (Adler and Colbert, 2013).

It is used to alleviate symptoms of certain diseases, such as nausea and vomiting, in cancer patients who are undergoing chemotherapy in many countries around the world (Malik et al., 2020). Malik et al. (2020) hypothesizes that CB1 (Cannabinoid receptor) is responsible for alleviating these symptoms since the inactivation of CB1 leads to vomiting, and when *C. sativa* is administered, this receptor is activated; thus, nausea and vomiting are treated or inhibited. Cannabinoid are a group of biological compounds found in *C. sativa* plants and have the ability to bind to cannabinoid receptors in cells (National Library of Medicine, 2024). There are over 100 different cannabinoids identified in *C. sativa*, and two of the most well-known ones are Tetrahydrocannabinol (THC) and Cannabidiol (CBD) (Malik et al., 2020; National Library of Medicine, 2024). The main distinctions between THC and CBD lie in their effects and receptor interactions. Tetrahydrocannabinol possesses psychoactive properties, inducing a "high," while CBD is non-psychoactive (Pennypacker and Romero-Sandoval, 2023). Additionally, THC has an affinity for binding directly to CB1 receptors, primarily located in the brain and central nervous system, contributing to its psychoactive effects (Perry et al., 2018; Pennypacker

and Romero-Sandoval, 2023). In contrast, CBD typically interacts with these receptors in an indirect manner, having a lower affinity for both CB1 and CB2 receptors in the endocannabinoid system. (Perry et al., 2018; Pennypacker and Romero-Sandoval, 2023).

Cannabidiol is the subject of research for its potential therapeutic benefits, including anti-inflammatory, analgesic (pain-relieving), anxiolytic (anxiety-reducing), and antipsychotic properties (Malik et al., 2020; Naftali et al., 2013). It is commonly incorporated into wellness products. On the other hand, THC is known for its medical applications, such as alleviating pain, controlling nausea, stimulating appetite, and reducing muscle spasms (Stockings et al., 2018). It is occasionally used in medical *C. sativa* treatments for specific conditions. These differences highlight the unique properties of each cannabinoid, influencing their roles in medical and wellness contexts.

Cannabis sativa is used to alleviate pain caused by a number of conditions such as cancer, HIV, diabetes, arthritis, multiple sclerosis, etc. (Stockings et al., 2018). It can reduce spasms in patients suffering from multiple sclerosis and is used to treat people suffering from epilepsy (Corey-Bloom et al., 2012; Stockings et al., 2018). Studies found that *C. sativa* has the ability to inhibit the growth of tumours by facilitating apoptosis (cell death), thus preventing some cancers from forming (Pisanti et al., 2009). Preliminary studies on medicinal benefits of *C. sativa* illustrate that it can alleviate or treat some conditions despite the limited research in this field.

1.1.4 History of Recreational use

The recreational use of *C. sativa* has a long history dating back thousands of years (Abel, 1980). In its long history, it has been vilified by some, while others had only good things to say about the plant. In some societies and religions, it was prohibited; a good example was Confucius China and the Catholic Church of Medieval Europe, while in India and the Rastafari movement in Jamaica the use of this plant was permitted in religious settings and for recreational use (Li, 1974; Pretorius, 2006; Warf, 2014). As time passed and different leaders came into power, societies across the globe slowly started to view the recreational use of *C. sativa* in a negative light. The post-revolutionary era in the United States of America, farmers were encouraged to plant *C. sativa* (recreational and hemp) not only for its recreational use but mostly for its industrial use in making clothes, ropes, sails, etc. (Warf, 2014). The negative view of *C. sativa* started in the late 19th century to the early 20th century when it was viewed as a drug used by mostly minorities such as Latinos and African Americans and was associated with an increased crime rate (Galliher and 1982; Warf 2014). This culminated in the enacting of laws that prohibited its use in many countries across the globe (Himmelstein, 1983; Sloman, 1999; Warf, 2014). Its prohibition in the US was fueled by the cotton farmers who feared competition from hemp production (Bonnie and Whitehead, 1970, Galliher 1982; Baum, 1996).

The recreational use of *C. sativa* increased in the US during the 1960s when middle-class, university students and white Americans started using it (Albeson et al., 1977). The Vietnam War played a role in the increased use of marijuana (*C. sativa*); anti-war activists such as hippies (A counterculture that formed in the USA and was opposed to war) regularly used *C. sativa* for recreational use (Smead, 2000; Warf, 2014). The growing number of *C. sativa* users led to its decriminalisation in many states and countries. In some states like Colorado and countries like Canada, recreational use *of C. sativa* has been legalized, and countries like South Africa have permitted the private use of *C. sativa*, thus opening up a whole new industry.

This new *C. sativa* industry is poorly understood because, for the better part of the 20th century, it was illegal and thus, there is little to no research about it. One of the key points of research is its water use, and this is especially important here in South Africa since it is a water-scarce country (Hellberg, 2019).

1.2 Aims

To investigate and better understand the water use of *Cannabis sativa* so that future decision making is informed about its cultivation by legacy farmers in rural and underdeveloped areas of the south Eastern regions of South Africa.

1.3 Objectives

1. Establish a cultivation framework for *Cannabis sativa* under dryland conditions by growing *C. sativa* in an open field, simulating traditional agronomic practices observed among legacy farmers in the Eastern Cape and KwaZulu-Natal. This step sets the foundation for understanding the water use patterns of *Cannabis sativa* in conditions reflective of historical farming practices.

2. Determine the evapotranspiration rate from a canopy of both *C. sativa* and a dominant, indigenous perennial grass *(Eragrostis plana)* using a large aperture scintillometer. Conduct a comparative analysis of the water use characteristics between the two plant species within the study site. *Eragrostis plana* was selected as it is the dominant landcover which occurs in abandoned arable land in the rural areas of the Eastern Cape. This objective directly builds on the cultivated conditions established in the objective above and aims to quantify and compare the water use of *C. sativa* and *E. plana.*

3. To measure several biophysical parameters of *C. sativa*, including stomatal conductance (g_s), plant height, plant width, and leaf area index, across a wide range of growth stages and environmental conditions. These measurements will provide insights into the overall production of the plant, as these parameters are indicative of its well-being. This objective is closely linked to the first objective, as the

collection of these physiological parameters becomes possible once the plants have grown in the cropping area.

4. To parameterize and validate an evapotranspiration model (MEDRUSH). This model, once validated, can be employed to simulate water use not only within the study site but also in other locations. This objective connects with the data obtained in Objective 3 (stomatal conductance), as the model will be utilizing stomatal conductance and meteorological data to predict evapotranspiration.

5. To describe in detail the meteorological parameters of the study area to make informed decisions about regional up-scaling of *C. sativa* cultivation by collecting and analysing key meteorological factors such as temperature, relative humidity, radiation, wind speed, and precipitation. This information will contribute to an improved understanding of the risks of dryland cultivation, providing essential context for interpreting the water use patterns observed in *C. sativa* and *E. plana.* The differences between the evapotranspiration rates of these two species will demonstrate the likely differences in large scale cultivation on catchment scale run-off and return flows to rivers and groundwater.

Chapter 2. Theoretical Background

2.1 Literature review

2.1.1 Hemp and medicinal *C. sativa*: the main difference

The word hemp has been in use for centuries and it was generally used to describe any fibre (West, 1998). West (1998) suggests that the word hemp was first used to describe *C. sativa* in the 1890s when the word hemp-marijuana was first coined and later adopted by the bureau of Narcotics (USA) in the 1930s. This linguistic evolution has led to considerable confusion among both the general public and policymakers, as the distinction between the two was blurred. The main difference is that hemp or fibre variety of *C. sativa* is specifically bred for its fibrous stalks, which are rich in cellulose and used in various industrial applications such as textiles, paper, and construction materials (West, 1998). These hemp fibre varieties typically have tall, sturdy stalks with minimal branching and produce relatively low levels of cannabinoids, including THC and CBD (Gill et al., 2022). Due to its morphological characteristics with thicker stems and larger leaves, hemp fibre possesses a greater surface area for photosynthesis and transpiration, potentially resulting in higher water use (Gill et al., 2022; Duong, 2023). In contrast, other varieties of *C. sativa*, commonly referred to as marijuana or medicinal cannabis, are cultivated primarily for their psychoactive or medicinal properties, with a focus on the flowers and leaves rather than the stalks (West, 1998; Pennypacker& Romero-Sandoval, 2023).

2.1.2 *Cannabis sativa* water use

Water is one of the most essential resources on Earth, and it has been under severe pressure due to anthropogenic activities, and this has led to freshwater scarcity (Pidcock, 2016). The Department of Environment Affairs (DEA) Long Term Adaptation Scenario (LTAS) report (2013) paints a bleak picture for South Africa's water resource future if emissions are not significantly reduced. The LTAS (2013) report suggests that there will be increased runoff and extreme flooding in KwaZulu Natal, southern Mpumalanga, and Eastern Cape if emissions remain unmitigated. While the southwest and western regions of the country will be faced with increased evaporation, decreased rainfall, and drought conditions. The LTAS (2013) report further suggests that the severity of these extreme weather conditions could be reduced if global emissions are significantly cut to less than 450 ppm carbon dioxide (CO_2) by mid-century. This water problem is not unique to South Africa; it is a global phenomenon. Water scarcity has been reported across the globe, from China to Spain to the United States of America. It is, therefore imperative that the global community finds practical ways to reduce global emissions significantly in order to avert extreme weather conditions such as droughts, that will adversely affect the world's agricultural production, people's livelihoods and the environment.

Agriculture is the largest consumer of freshwater through irrigation schemes (FAO, 2020). Water use efficiency is defined by Hatfield and Dold (2019) as the amount of carbon assimilated as biomass or grain produced to the amount of water utilized by the crop. *Cannabis sativa* is understood to be a species that uses significant amounts of water and has the potential to reduce stream flows and cause significant reduction in groundwater (Deitch et al., 2009; Dillis et al., 2020). With the relaxation of laws governing *C. sativa* across the world, it is expected that cultivation of this plant will increase rapidly thus putting further strain on the already scarce water resource. It is against this backdrop that many studies looking into its water use have been commissioned.

In South Africa, water use is governed by the National Water Act of 1998 and the National Water Amendment Act of 2014. The primary purpose of this Act is to avoid or minimize adverse impacts on the water resources of the Republic of South Africa (Department of Water Affairs, 1998). These adverse impacts include, amongst many, the over-exploitation of water resources for agricultural, mining and industrial purposes, thus leading to reduced streamflow and disruptions at the catchment area level (DWA, 1998). The Department of Water and Sanitation is responsible for granting water use licenses (Department of Water and Sanitation, 2022) to regulate catchment-scale water use. The water use licenses are granted upon the completion of a rigorous investigation into the water use of each agricultural or silvicultural crop. The competent authority of the Department will grant or refuse the water use license based on how the crop affects the water resource or catchment area (DWS, 2022). At present, information on how *C. sativa* affects streamflow and the amount of water it uses is still being determined. Therefore, by shedding light on its water use, the Department can determine whether a full water use license application is needed or not.

According to preliminary findings from California, *C. sativa* cultivation may be using substantial amounts of water (Bauer et al., 2015). As it currently stands, the amount of water it uses is quite ambiguous. However, there have been a limited number of studies conducted in the Northern Hemisphere, especially in California, a relatively dry region of the United States West Coast (Bauer et al., 2015; Dillis et al., 2020). These studies corroborate claims that the plant is water-thirsty and uses a significant amount of water during its growth cycle. California is a winter rainfall region, and as *C. sativa* is a summer crop, all the growth in California is fed by irrigation only (Bauer et al., 2015). A study conducted by Butsic and Brenner (2016) sheds light on the water consumption patterns associated with the cultivation of *C. sativa* in different environments. Their findings indicate that under outdoor cultivation in northern California 757 plants used approximately 1740m^3 of water over a span of 150 days (15.32 mm $plant^{-1}$ day^{-1}), whereas under indoor greenhouse cultivation, 960 plants consumed around 2218 m^3 of water during the same timeframe (15.4 mm $plant^{-1}$ day^{-1}. Notably, the greenhouse cultivation method tends to accommodate a greater number of plants, averaging at 85.77

± 88.81 plants, compared to outdoor cultivation, which had fewer plants with an average of (67 ± 75) (Butsic and Brenner, 2016). The variation in plant numbers could contribute to the observed disparity.

In the same region of California, *C. sativa* has been cultivated for some time, and because of the legal status of the plant, there is a dearth of water use results of *C. sativa* (Dillis et al., 2020). Despite this lack of information on the water use of *C. sativa*, Dillis et al., (2020) suggest that it has the potential to reduce freshwater resources in the region and significantly affect aquatic life in freshwater ecosystems. A study conducted on farms in northern California has revealed that water usage is higher in mixed indoor farms due to the high density of plants as compared to the outdoor farms, but both farming methods revealed decrease in water extraction during the summer dry season due to using stored water (Dillis et al., 2020). Despite this decreased extraction in dry season*, C. sativa* still exhibits highly variable water use (Dillis et al., 2020). Lisson (1998) suggests that significant irrigation is needed in areas where the amount of rainfall is low or un-predictable. This would mean that dry regions like southwest Spain and some regions of South Africa will face challenges in cultivating *C. sativa* (DAFF, 2011; Garcia-Tejero et al., 2014). Garcia-Tejero et al. (2014) conducted a study in south west Spain and found that at 100% irrigation, the yield of *C. sativa* depended on the density and cultivar used. This further corroborates previous studies that water is a limiting factor because without irrigation, as observed by Lisson (1998), the yield would be significantly lower or crops may fail. This raises questions on the viability of this plant in water-scarce country like South Africa.

Despite this concern about the plant's water consumption, there have been some promising results in the Mediterranean, where it was discovered that the production was high for *C. sativa* (Cosentino et al.,2012). The high yield was partly due to the planting season, i.e., planting during seasons where days are longer; thus, plants receive more sunlight (Cosentino et al., 2012). This would be beneficial for parts of South Africa like the Eastern Cape, since most days in this province have clear skies with sufficient sunlight. Consentino et al. (2013) discovered that water consumption dependent on the type of *C. sativa* that was being planted e.g., monoecious plants which is a plant with male flowers and female flowers in separate structures on the same plant, needed less water when compared to dioecious which is a plant that has either male or female member. Dillis et al. (2020) also found that plants grown in high-density settings exhibit increased water consumption.

2.1.3 Water-use in South Africa

In the 2022 State of the Nation Address, President Cyril Ramaphosa spoke of the need to speed up the processes of legalizing and issuing licenses for *C. sativa* cultivation (SONA, 2022). This comes after years of court proceedings and delays. One of the key issues in *C. sativa* cultivation is its water use and according to the Department of Agriculture, Forestry and Fisheries (2011), South Africa is a water-

scarce country, receiving an average annual rainfall of about 464 mm, which is below the world average of 786 mm. It is therefore imperative for the South African Government to have knowledge on the amount of water the plant uses in dryland areas of South Africa. This knowledge is vital because it will inform the decision to grant or reject a water use license by the Department of Water and Sanitation. The Premier of Eastern Cape in his State of the Province Address reiterated the need for inclusive legislation that will include indigenous or so-called 'legacy growers'. These indigenous growers are mostly located in the Mzimvubu River Valley in the O.R. Tambo District of the Eastern Cape. This area is situated on the eastern side of Eastern Cape and South Africa and receives higher rainfall when compared to the western side and interior of the country (Mahlalela et al., 2020). This rainfall disparity has to be taken into account when cultivating *C. sativa*. *Cannabis sativa* has been historically cultivated by legacy growers across South Africa, especially in the eastern regions of the country, which include the northeast part of the Eastern Cape, KwaZulu Natal and parts of Mpumalanga Provinces. South Africa faces the same challenges as the rest of the world when it comes to *C. sativa* cultivation in that there is a dearth of literature. This is because of past laws that criminalised the plant thus inhibiting any studies especially its water use. This is thus a new field of study and South Africa has just come to terms with its water shortages. Merely three years ago, Cape Town, the second-largest city in South Africa, confronted severe water shortages, narrowly avoiding disaster through the implementation of strategies aimed at reducing water usage (Taing et al., 2018). This highlights the critical water situation in South Africa. Many parts of the Eastern Cape Province are faced with the same problem of severe water shortage due to a protracted drought, and it is not any different in other parts of the country (Mahlalela et al., 2020) (Figure 1). This illustrates how water-stressed South Africa is, and this is compounded by poor water management, ageing infrastructure and an increased population (Taing et al., 2018; Mahlalela et al., 2020). This means any new proposed development has to come with well-defined sustainable water usage strategies for it to work optimally. The proposed cultivation of *C. sativa* in the Eastern Cape and KwaZulu Natal must demonstrate that the plant is not going to put pressure on the already strained water resources of the region.

Water is a limiting factor, especially in the western parts of the Eastern Cape, where mean annual rainfall is between 450-550 mm per annum (Nelson Mandela Bay Metropolitan Municipality, 2022). The largest city in the Eastern Cape Nelson Mandela Bay, which is situated on the western side of the province, is grappling with a crippling drought and is a few months or weeks from reaching day zero, i.e., when the taps run dry if no significant rainfall occurs (Nelson Mandela Bay Metropolitan Municipality, 2022). Already, there are areas in Ngquza Hill local municipality, such as the Mantlaneni Village, where river water is pumped into the *C. sativa* fields for irrigation purposes (Lewis, 2020). A

significant concern is that there are no studies yet to reveal the amount of water extracted from the river and how this extraction affects aquatic life and the river's streamflow. This illustrates the necessity of understanding the water utilization patterns of *C. sativa* prior to its authorization for widespread cultivation.

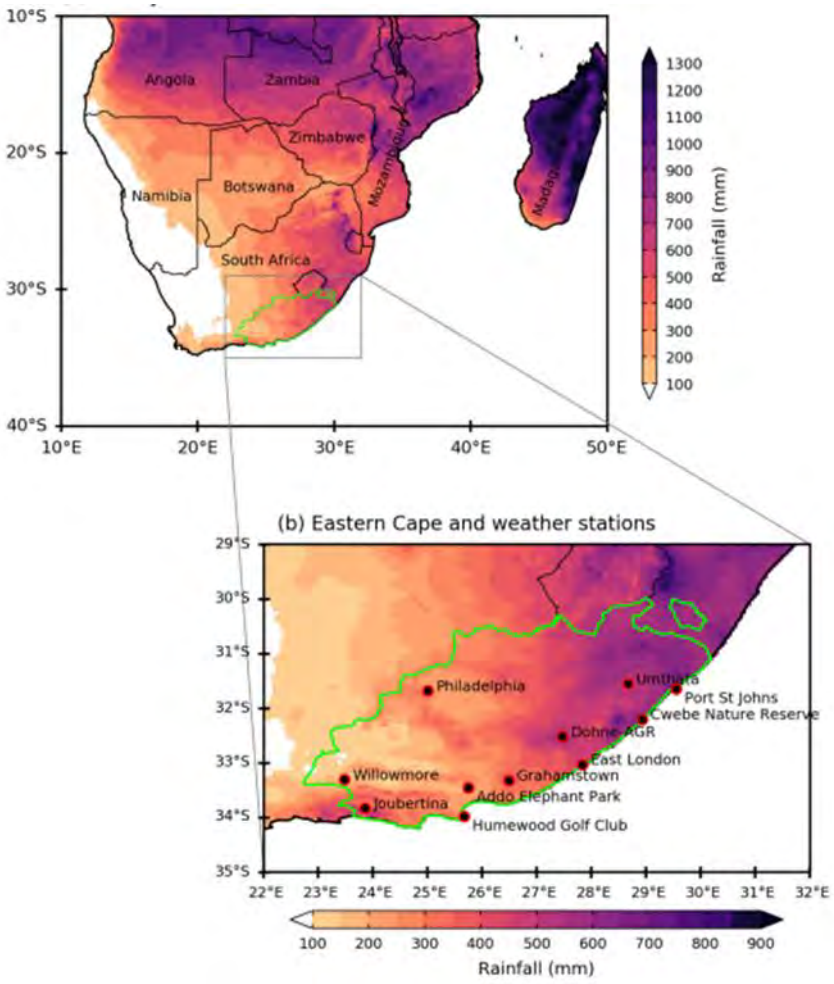

Figure 1: The rainfall patterns in South Africa and the Eastern Cape, depicted in the green polygon, show that the eastern half of the Eastern Cape receives more rain than the western half (Mahlalela et al., 2020).

2.1.4 Socioeconomic and Ecological effects of *Cannabis sativa*

Cannabis sativa has a long history of being used as a crop to generate income and make a living, i.e., a cash crop (Clarke and Merlin, 2016). The plant has a wide range of uses ranging from textile fibre to food products and medicinal purposes (Hanegraaf et al., 1998; Johnson, 2014; Shams et al., 2020). *Cannabis sativa* as a cash crop presents multiple opportunities, especially for the developing world (Wimalasiri et al., 2021). The Eastern Cape Government has drawn up plans to ensure that rural communities benefit from selling *C. sativa* (South African Parliament NCOP, 2022). *Cannabis sativa* with a high THC content (medicinal and recreational) can generate up to R 150000 per hectare per year, and the average legacy grower who cultivates half a hectare could potentially receive an income

of about R 75000 per year (Lewis, 2020). The Eastern Cape Provincial Government's current initiatives include *C. sativa* farms in Alfred Nzo and OR Tambo District Municipalities. These farms include Sigidi Development Project, Tashe Cannabis Project and Ndwendwe Farming Cooperative, all situated in Alfred Nzo District Municipality (South African Parliament NCOP, 2022). Despite the increased interest from local authorities and international markets for *C. sativa* grown in the region, local farmers are still faced with tough challenges, including expensive licenses, legal status and subsequent harassment from local law enforcement (South African Parliament NCOP, 2022). A parliament delegation visited the region's various farming areas and heard the challenges local growers face (South African Parliament NCOP, 2022). They assured the growers that measures are being put in place to ensure that they are able to farm successfully and sell their produce (South African Parliament NCOP, 2022). *Cannabis sativa* cultivation has immense economic potential because it is a relatively easy to cultivate and in dryland conditions, can be grown without commercial fertilizers or elaborate irrigation systems. It is an annual crop that is produced in the first year of cultivation as opposed to fruits and nuts, which take longer and require significant inputs (Lewis, 2020). It is easy to transport, does not easily get damaged in transit, and has many uses (Lewis, 2020).

Cash crops have lifted millions of people out of poverty in the developing world and enabled them to play an active role in the world economy (Li et al., 2018). The cultivation of *C. sativa* can play a significant role in upliftment thousands of rural people out of poverty in the Eastern Cape and other less developed areas of South Africa, but all this needs to be done in a sustainable manner that will ensure that people benefit and the environment, i.e., water resources, are not put under severe stress thus leading to reduced water availability for people and aquatic organisms.

2.1.5 *Cannabis sativa* Growing Conditions

The growing conditions of *C. sativa* vary widely from region to region and are controlled by various parameters or factors from the genetics of the plant, temperature, soil moisture, soil pH, wind, relative humidity, radiation, time of planting, daytime length and harvesting (Denmead, 1984; Cosentino et al.,2012; Saugier and Katerji; Desanlis et al., 2013; Prato et al., 2022). The plants perform differently in temperate regions like Europe and USA when compared to the tropics and subtropics like Australia (Prato et al., 2022). In the Northern Hemisphere, the plant must be planted below 50˚ N; in the Southern Hemisphere, it is unknown due to the lack of research in this field due to its legal status and financial constraints (Chandra et al., 2017). The little available information comes mainly from Europe and America, although Australia and China have limited, although burgeoning, research sector. Indoor growing conditions are different from outdoor conditions (Denton et al., 2001). Indoor facilities tend to apply more inputs as compared to outdoor cultivation (Denton et al., 2001). A good example is the use of root hormones applied to cuttings before they are sown into the soil during indoor cultivation

(Chandra et al., 2017). This is in stark contrast to many outdoor cultivations whereby growers try to use as few inputs as possible. The difference in water usage is substantial, as evidenced by a study conducted in northern California, USA. Indoor facilities, were found to consume approximately 2218 m^3 of water, whereas the largest outdoor facility utilized about 1740 m^3 of water. Interestingly, despite indoor cultivation averaging 86 plants and outdoor cultivation averaging 67 plants, the authors do not explicitly attribute the difference in water usage to the varying plant numbers (Bustic and Brenner, 2016)). These are just two examples of many, that illustrate how input intensive are indoor growing facilities as compared to outdoor ones.

2.1.6 Growing conditions for *Cannabis sativa* in different Regions of the World

One of the most critical inputs in growing any plant or crop is nutrients, and it is no different for *C. sativa*. Bocsa and Karus (1998) state that nitrogen is essential in *C. sativa* growth and is required in large quantities. This statement is corroborated by the findings made by Prato et al. (2022), whereby nitrogen of 150 ha^{-1} resulted in the tallest plants and with the heaviest dry roots. This was accompanied by increased shoot weight and base stalk with increasing nitrogen. Desanlis et al., (2013) recommends the application of about 100 kg ha^{-1} of nitrogen in a field, but the study in Australia showed that a higher volume of 150 kg ha^{-1} produced more yield when compared to 50 and 100 kg ha^{-1} of nitrogen (Prato et al., 2022). The difference in the nitrogen quantities could be attributed to other factors, such as water availability and the lack of other micro and macronutrients. Soil temperature plays a crucial role in *C. sativa* growth, it is especially important in seed emergence (Prato et al., 2022). Roberts (1988) found a direct correlation between increased temperature and germination rate. A temperature of 27 ˚C during the day and 24 ˚C during the night is recommended in the subtropics and tropics for optimum *C. sativa* growth (Prato et al., 2022). Chandra et al. (2017) offers a range of temperatures at which *C. sativa* grows optimally; with a daily average of 25 ˚C to a high of 35 ˚C.

The choice of genotype is very important, because with the suitable and well-adapted genotype to that particular area or region, there will be no need for numerous inputs such as high amounts of nutrients such nitrogen, root hormones, and artificial lighting (Chandra et al., 2017; Prato et al., 2022). The place of origin of a particular *C. sativa* variety is critical. In the study conducted in the subtropics, a variety called Morphet, originally from temperate areas did not do well when compared to subtropical varieties in Australia. It was found that the temperate variety was significantly shorter, had less dry weight and its emergence time was longer (Prato et al., 2022). Amaducci et al. (2015) indicates the importance of genotype, this is due to the fact that *C. sativa* is photoperiod dependent, photoperiod refers to the length of time during a 24-hour period that an organism is exposed to light, it varies according to season and latitude (Jackson, 2009). For example, cultivars grown in the Northern Hemisphere have lower biomass yield when grown in the Southern Hemisphere, this because of the

shorter growth time and early flowering (Meijer et al., 1995; Yao et al., 2007; Amaducci et al., 2008b; Cosentino et al., 2013; Guo et al., 2013). These finding corroborate those found by Prato et al. (2022).

Soil is another important factor in the successful growing of *C. sativa*. Chandra et al. (2017) used peat-soil mixture which is high in organic matter for sowing their *C. sativa*, this mixture yielded good results. While Struick et al. (2000) and Amaducci et al., (2015) suggest that soil preparation is essential before any cultivation can take place. A seed bed needs to be established; this will aid in obtaining the best plant density. Good soil preparation encourages water and nutrient absorption which results in good growing conditions for *C. sativa* (Desanlis et al., 2013). Ploughing in winter to depths of between 30-40 cm followed by seed bed preparation in spring and then sowing can commence. This method is highly recommended, especially in clay soils (Desanlis et al., 2013). *Cannabis sativa* requires deep well aerated soils that can retain water and are rich in micro and macro nutrients (Amaducci et al., 2015), Li (1982) indicated that the best soils to grow *C. sativa* are sandyloam and clayloam while clay and sandy soils were not good for growing *C. sativa*. The inferior quality of clay is linked to its tendency to compact, which in turn impedes the growth of *C. sativa* (Amaducci et al., 2015). Conversely, sandy soil exhibits poor water retention capacity, thereby depriving the plant of essential moisture (Amaducci et al., 2015).

Soil pH is also important, a soil pH of 6 and 7.5 is recommended (Amaducci et al., 2015). These findings corroborate the findings of the study done by Desanlis et al. (2013) whereby a pH of 6 is recommended for optimum growing conditions.

Sowing time is very important and it is specific to a geographic region (Amaducci et al., 2015). In the Mediterranean region it is recommended that sowing should commence February to March i.e., Spring time (Di Bari et al., 2004). Certain regions of South Africa share a climate akin to the Mediterranean. For these areas, the optimal sowing time typically falls between late August and September. However, this timing may not be applicable across the entire country, as other regions lack the extended daylight hours characteristic of the Cape provinces, including Eastern Cape, Northern Cape, and Western Cape. Ammaducci et al. (2008) recommends sowing as early as possible. Fertilizer should be applied in Spring just before sowing commences, a depth of 2-3 cm for seed sowing and a distance between the seeds of 9 to 17 cm is recommended (Finnan and Burke, 2013). Finnan and Burke (2013) suggest a seeding rate ranging from 40 to 65 kg/ha in order to get 200 to 300 plants/m^2 for hemp.

High temperatures accompanied by drought conditions can lead to stunted growth and early flowering (Amaducci et al., 2008). This further indicates the importance of water management in *C. sativa* cultivation. Bocsa and Karus (1998) propose that hemp cultivation in Europe necessitates a daily moisture intake ranging from 500 ml to 700 ml to achieve optimal yields. Notably, hemp varieties

require slightly more water compared to other types of *C. sativa*, suggesting the potential for reduced water consumption by medicinal *C. sativa* variants. This indicates suitability for cultivation in regions like the Eastern Cape of South Africa, which frequently experiences drought conditions. Conversely, Consentino et al. (2012) advocate for a water requirement of 450 ml per day for *C. sativa* cultivation in semi-arid areas. Some varieties of hemp like Futura 75, did not exhibit any changes when water was reduced (Amaducci et al., 2015). This sharply contrasts with the findings presented by Hojgaard (2021), who observed that legacy farmers in Mpondoland irrigated their crops, especially for the high-grade strain. This aligns with the conclusions drawn by Consentino et al. (2012), asserting that *C. sativa* exhibits a reliance on a continuous water supply for sustained vitality, optimal growth, and ultimately, a good yield.

However, it's important to emphasize that the crops grown in Mpondoland are not hemp, but rather intended for recreational and medicinal use due to their high THC content.

2.2 Evaporation

Water is one of the most important substances on Earth, as previously mentioned in the literature review sub-chapter (Flint, 2004; Pawlowicz and Yerubandi, 2024). Water is one of the key reasons this planet is habitable and hosts a wide variety of life (Flint, 2004). For this planet to continue to be habitable there must be a constant supply of water (Hanslmeier, 2011). This constant supply water is dependent on the hydrological cycle, which is a continuous circulation of water in various phases of matter between the surface and atmosphere (Oki and Kanae, 2006). One of the most important processes in the hydrological cycle is evaporation (Monteith, 1965; Oki and Kanae, 2006). Allen et al. (1998) define evaporation as the loss of water from a surface such as a lake, river, wet pavement, wet plants, and the ocean. In its most fundamental definition, it is the change from the liquid phase to the gaseous phase (Allen et al., 1998; Datt, 2011). Evaporation is influenced or driven by four main factors: radiation, relative humidity, wind speed, and temperature (Ritjema, 1965).

Datt (2011) suggests that this process is largely driven by energy in the form of radiation, the energy enables the change from liquid to gaseous phase in a process termed vaporisation. The air above must possess low relative humidity to carry an increased load of water vapor, requiring higher wind speeds to disperse the vapor and create space for additional water vapor accumulation (Farhat, 2018). Hence, wind speed and relative humidity emerge as pivotal factors alongside temperature and radiation (Allen et al., 1998). This interplay underscores the significance of these parameters in the formulation of evapotranspiration models and formulas for accurate evaporation estimation.

2.2.1 Transpiration

The human population is expanding rapidly and the need to produce more crops per unit of water has never been this important in human history (Vadez et al., 2014). This increasing demand for agricultural productivity places an unprecedented strain on water resources. Vadez et al. (2014) argue that one of the ways to reduce this strain on water resources is to rigorously study the transpiration of different crops and their genetics, thus enabling researchers and agronomists to know which plant variants require less water. This shows the importance of transpiration in the conservation of water.

Transpiration is defined as the process by which water is absorbed by plants from the soil, moves through the plant in specialised vascular tissue called the xylem, and is released into the atmosphere in the form of water vapor through microscopic openings on the abaxial surface - called stomata and which are regulated by two guard cells (Allen et al. 1998; Lumen learning, 2022). The water content of the plant determines the rigidity of the guard cells, and thus the size of the opening between them, thus regulating the exchange of carbon dioxide and water vapour between the external atmosphere and the air space within the leaf.

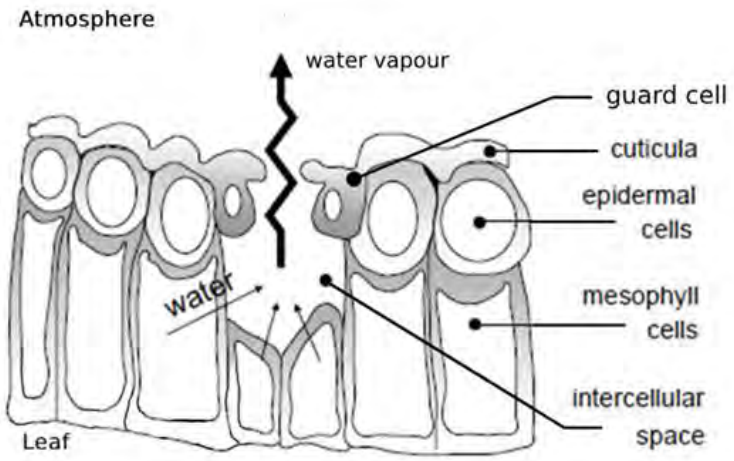

Figure 2: Showing water movement in a plant (edited from Allen et al. 1998)

According to Allen et al. (1998) only a fraction of water remains in the plant for plant uses such as nutrient transportation, photosynthesis, turgor pressure, temperature regulation, metabolic reactions and cell expansion, while most of the water is lost through transpiration. The process of transpiration is driven by energy in the form of radiation, wind speed, relative humidity and vapour pressure gradient, soil and genetics (Allen, 1998; Vadez et al., 2014). All these parameters play a vital role in transpiration of water from plants.

2.2.2 Evapotranspiration

Evapotranspiration (ET) studies play a crucial role across ecological, agricultural, hydrological, and climatological disciplines, as emphasized by Liu et al. (2013) and Krishna (2018). These studies hold significance in various domains, including water resource management, agricultural water use efficiency, climate modelling, ecosystem health, water balance, drought monitoring, land use planning, carbon and energy balance research, and remote sensing applications (Mohan and Arumugam, 1996; Liu et al., 2013). By comprehensively understanding and quantifying evapotranspiration, valuable insights are gained into water losses from soil and vegetation, facilitating effective water resource management (Liu et al., 2013; Krishna, 2018).

In agriculture, these studies optimize irrigation practices, enhance water use efficiency, and inform sustainable approaches by understanding the water needs of different crops. Despite its pivotal role, the understanding of this process remains limited owing to the intricate and multifaceted nature of evapotranspiration (Krishna, 2018). Evapotranspiration is a complex process. This complexity arises from factors such as plant physiology, the constituent elements of ET (transpiration and evaporation), environmental variables like weather, soil type, and land management, as well as the intricacies introduced by the models employed to measure ET. Farahani et al., (2007) suggest that improvement in technology and measuring techniques have contributed to better understanding of ET process, indicating a gradual progression toward enhanced comprehension. With the advent of technologies such as artificial intelligence, there is a promising trajectory towards more accurate measurements and model predictions in the field. Evapotranspiration is fundamentally defined as the combined process of water vapor movement into the atmosphere through both evaporation from open water or soil surfaces and transpiration from plants (Irmak and Haman, 2003). This flux is a key parameter in understanding the relationship between the atmosphere, soil, and vegetation; thus, determining the rate of transfer has enabled researchers, agronomists, and extension officers to better understand the effects various crops and plants have on water dynamics (Liu et al., 2013).

Evapotranspiration is made up of the combination of two similar processes, evaporation and transpiration (Allen et al., 1998), and the contribution from each process is tied to the developmental stage of the vegetation in the landscape. When plants are small, the bulk of ET is from soil evaporation since it will be more exposed to radiation and other meteorological elements. As plants mature and develop canopies, transpiration becomes the primary contributor, to ET (Allen et al., 1998). Both processes involve water loss or release into the atmosphere; the key difference is the source of the evaporating water.

2.2.3 The difference between Actual ET, Potential ET and Reference ET

These are terms used to describe evapotranspiration components (Troung, 2012). Each component considers various physical factors in its assessment. They represent different aspects of the water loss process from the land surface and are crucial factors in hydrological and agricultural studies, particularly in understanding water balance and estimating water requirements for crops and vegetation (Troung, 2012).

The Actual ET (AET) is defined as the quantity of water vapour released from the soil and vegetation when the environment and soil are at their natural moisture content (World Meteorological Organization (WMO), 1992). A lysimeter is one the methods used to measure actual evapotranspiration; it measures the weight of a soil sample overlain by vegetation by measuring the inflow and outflow of water from the soil (Shuttleworth, 2008). The lysimeter is suitable for an area well covered by vegetation and to a scale of a plot. However, it may prove challenging to use it in a large study area, and its installation may disturb the soil and vegetation, thus yielding unreliable results (Shuttleworth 2008; Troung 2012). Nonetheless, alternative methods for measuring Actual Evapotranspiration (AET) do exist, including the water balance method (Xu and Singh, 2005). This approach is commonly employed on a large scale, such as at the catchment scale, to estimate AET (Xu and Singh, 2005).

The Potential ET is defined as the quantity of water vapour that would be lost from a plant and soil surface if there was unlimited supply of water (Hansen et al., 1980; Dingman 1994, Watson and Burnett 1995). While Penman (1948) defined PET as the amount of water transpired by a short green crop, completely shading the ground of similar height and with sufficient water supply in the soil surface. In essence, PET encapsulates the maximum potential water loss from both plant and soil surfaces, considering the atmospheric demand for moisture and the physiological characteristics of vegetation

To overcome limitations associated with AET and PET, the Reference Evapotranspiration (RET) method was devised. Unlike the former methods, RET is independent of factors such as soil or vegetation and relies solely on meteorological data. This approach creates a standardised, surface for comparison to other surfaces, such vegetation and bare soil. (Jensen et al. 1990, Allen et al. 1998). Irmak and Haman (2003) define RET as “the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sec m^{-1}, and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground”. The Penman-Monteith model is

recommended for computing RET as it relies on meteorological data rather than specific vegetation and soil characteristics, as in PET.

2.2.4 Factors affecting Evapotranspiration

There are multiple factors that affect the rate of evapotranspiration; chief amongst them is energy availability in the form of radiation, temperature, humidity, wind speed, land management practices, and the physical properties of vegetation such the height, leaf area index, the shape of the leaf and its reflectivity (Stancalie and Nertan, 2012). Each of these factors significantly contributes to the rate of evapotranspiration.

Primary among these influences is energy availability in the form of radiation and air temperature, these two are the primary drivers of evapotranspiration. An increase in temperature accelerate evapotranspiration by energizing water molecules in plants, prompting their conversion to the gaseous phase. (Troung, 2012; USGS, 2012). This causes the plant to open the stoma, during stomatal opening, water molecules in the mesophyll cells of the leaf undergo evaporation (Saugier and Katerji, 1991.). This process takes place within the leaf's internal structure, where water molecules transition from the liquid phase to a gaseous state. As these water molecules evaporate, they diffuse into the intercellular spaces and move toward the stomatal pores (WMO, 1990; Saugier and Katerji, 1991; Troung, 2012; USGS, 2012). This is driven by differences in water vapor concentration between the leaf's interior and the atmosphere, the water vapor diffuses through the stomatal pores and is released into the atmosphere World Meteorological Organization (WMO, 1990; Saugier and Katerji, 1991; Troung, 2012; USGS, 2012) Lower temperatures have the reverse effect, which is why the summer months experience the highest rates of evapotranspiration (Troung, 2012; USGS, 2012).

Wind speed plays an important role in evapotranspiration/Iincreased wind speed results in increase in evapotranspiration this is because higher wind speeds encourage the movement of saturated air, increasing vapour pressure deficit (USGS, 2012).

Relative humidity is different from the other parameters exhibiting an inverse relationship with evapotranspiration rates (USGS, 2012). Higher relative humidity means the air is saturated with water, and therefore there is no space for the evaporating water from the plant thus leading to reduced evapotranspiration rates (USGS, 2012).

The physical properties of vegetation determine evapotranspiration rates and dynamics. Plants with larger leaves have increased evapotranspiration when compared to plants with smaller leaves (Troung, 2012; USGS, 2012), highlighting the significance of plant morphology in influencing this process.

2.2.5 Stomatal conductance

Stomatal conductance (g_s) is defined as the rate at which gases such as CO_2, oxygen (O_2), and water vapour (H_2O) diffuse through stomata (Damour et al., 2010). This physiological phenomenon is key to plant survival, as it plays a dual role in temperature regulation and facilitates the process of photosynthesis (Damour et al., 2010). Stomatal conductance, the extent to which stomata are open, has a profound impact on various ecological processes, including those related to the radiation budget, water cycle, and carbon cycle. In terms of the radiation budget, stomatal conductance influences the absorption of solar radiation by plants (Damour et al., 2010). Open stomata facilitate the entry of carbon dioxide (CO_2) necessary for photosynthesis, a process that converts solar radiation into energy to fuel metabolic processes (Eberhard et al., 2008). Additionally, stomatal conductance contributes to temperature regulation by allowing the release of water vapor through transpiration (Driesen et al., 2020). This water vapor flux cools the plant, preventing overheating during sunny conditions.

In the context of the water cycle, stomatal conductance is a key driver of transpiration, the release of water vapor from plants into the atmosphere (Allen et al. 1998, Damour et al., 2010). This process plays a vital role in the movement of water from the soil, through the plant, and into the atmosphere. Stomatal conductance is indirectly linked to the water cycle through its influence on water uptake by plant roots (Liang et al., 2002; Liu et al., 2017). The rate at which stomata release water vapor affects the movement of water within the plant, influencing water absorption from the soil (Liu et al., 2017).

Regarding the carbon cycle, stomatal conductance plays a central role in the uptake of carbon dioxide during photosynthesis. Open stomata enable the entry of CO_2 into plant tissues, a crucial step in the conversion of carbon dioxide into organic compounds (Damour et al., 2010). This process not only fuels the plant's growth but also releases oxygen as a byproduct. Furthermore, stomatal conductance influences the carbon cycle by regulating the influx of carbon dioxide, impacting the capacity of plants to participate in carbon sequestration (Liu et al., 2017). Through photosynthesis, plants absorb and sequester carbon, contributing to the overall balance of carbon in the environment (Damour et al., 2010; Liu et al., 2017). In summary, stomatal conductance emerges as a pivotal factor linking plant physiology to essential ecological cycles, affecting solar radiation absorption, temperature regulation, water movement, and carbon sequestration.

2.3 Evapotranspiration Modelling

There are numerous evapotranspiration models utilised across the globe, some are empirically based while others are physically based (Fontenot, 2004). These models have varying accuracies, some require a number of input parameters while others require less parameters (Fontenot, 2004). An

example of an accurate ET model that requires multiple meteorological parameters is the United Nations Food and Agriculture Organisation Penman-Monteith Model (Allen et al., 1998). Other ET models require less parameters such as the FAO 24 Radiation Method that can be utilised when there is ample sunlight i.e., radiation and air temperature and there is no wind and humidity data available and yet still yield relatively accurate results (Doorenbos & Pruitt, 1977; Allen et al., 1998). In this project the MEDRUSH model was utilised for measuring ET. The MEDRUSH model was developed for measuring ET in the Mediterranean region later modified for different regions and landscapes, and has been applied to simulated historical climate (Osborne et al 2000) and the impacts of alien invasive species on water fluxes (Palmer et al., 2023).

Chapter 3. Methodology

3.1 Introduction

The study is based in a dryland location in order to have a similar environment as legacy farmers in the Eastern Cape. In the dryland experiment, *Cannabis sativa* seeds were sourced from the Eastern Cape Province. A Large Aperture Scintillometer (LAS), was used to measure the change in the refractive index of the atmosphere and it was fitted with ancillary instruments to measure meteorological parameters including wind speed, pressure and temperature (Kipp and Zonen, 2021). This has enabled us to determine the prevailing weather conditions in real time and the rate of evapotranspiration (ET) from the *C. sativa*. A MEDRUSH model was used to estimate ET and it was later validated against the LAS measured ET.

3.1.1 Map plan for experiment: Water Use of *Cannabis sativa*

This methodological plan outlines the steps involved in conducting the experiment to determine the water use of *C. sativa* under dryland conditions using a LAS and the MEDRUSH model, while also considering plant biophysical parameters and meteorological factors.

Objective 1: Establish Cultivation Framework

1) Site Selection: A suitable field for cultivation was identified in the Eastern Cape in Makhanda, Firglen Farm.
2) Cultivation Setup: Traditional agronomic practices observed among legacy farmers for growing *C. sativ*a were implemented. This included soil preparation by clearing the field of all shrubs and grasses, planting, and installing a drip irrigation system.
3) Monitoring: Cultivation activities, including irrigation schedules and weed management, were regularly observed and carried out.

Objective 2: Evapotranspiration Rate Comparison

1) Large Aperture Scintillometer Installation: The LAS was installed to measure evapotranspiration rates from the canopy of both *C. sativa and Eragrostis plana*.
2) Data Collection: Evapotranspiration data was continuously gathered using the LAS over two growing seasons, firstly for *E.* plana (2021/22) and then for *C.* sativa (2022/23).
3) Analysis: A comparative analysis of evapotranspiration rates between *C. sativa and E. plana* was conducted to determine water use patterns.

Objective 3: Physiological Parameters Measurement

1) Parameter Measurement: Stomatal conductance (g_s), plant height, width, and leaf area index (LAI) of *C. sativa* were measured at various growth stages.

2) Data Collection: Physiological parameters were recorded using appropriate instruments including an Accupar hand-help leaf porometer, a measuring tape and an Accupar ceptometer Analysis: biophysiological data were analysed to assess the growth and production of *C. sativa* plants over the growing period.

Objective 4: Model Parameterization and Validation

1) MEDRUSH Model Parameterization: Stomatal conductance and meteorological data were input into the MEDRUSH model.
2) Validation: The model's output was validated against observed evapotranspiration rates from the LAS data.
3) Model Refinement: Model parameters were refined based on validation results to improve accuracy.

Objective 5: Meteorological Parameter Determination

1) Meteorological Data Collection: A meteorological station was installed to collect comprehensive data on temperature, relative humidity, radiation, wind speed, and precipitation.
2) Data Analysis: Meteorological data were analysed to understand local climatic conditions and their influence on water use patterns in *C. sativa and E. plana.*

3.2 Study site

The study site is located on a farm situated in a valley about 21 km from Makhanda central business district (33°19’10’’ S 26°23’11’’E) Eastern Cape, South Africa (Google Earth, 2021). The area that was cultivated is approximately 10 m width and about 130 m in length. The aspect of the slope of the area is south west facing (Google Earth, 2021). The area had been previously used for cultivation a few decades earlier and was already terraced and cleared with few shrubs and grass remaining (Figure 3).

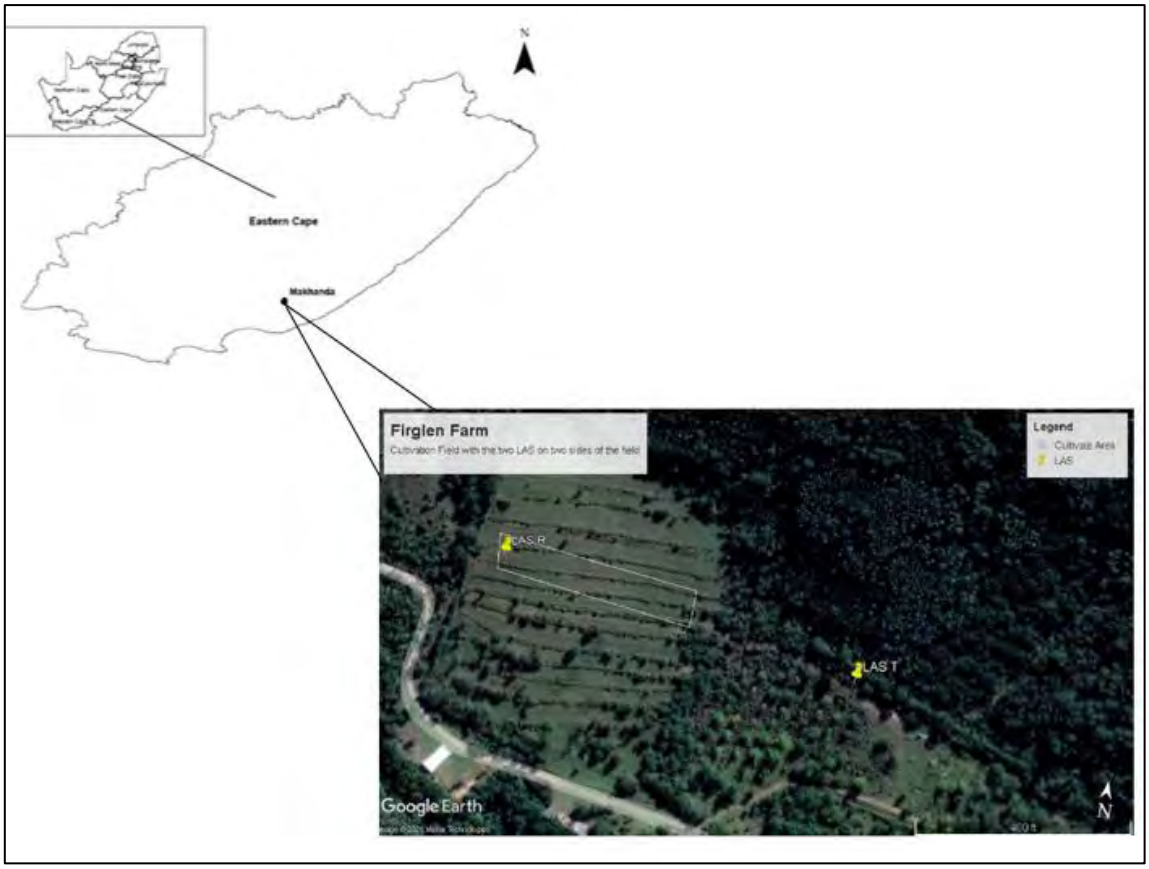

Figure 3: The study site at Firglen within the Eastern Cape Province, where the Large Aperture Scintillometer was installed. The yellow pins show the placement of the LAS receiver (LAS R) and transmitter (LAS T). The white box indicates the crop growing area

3.2.1 Climate

The climate of the area is semi-arid characterised by cold winters and hot summers with a temperature ranging from 0˚C and 40˚C (De Lacy & Shackleton, 2017). The annual rainfall from multiple sites in Makhanda from the late 19th century to the year 2012 and the modelled daily rainfall from the Climate Hazards Group InfraRed Precipitation with Station database (CHIRPS) (Funk et al., 2015) (Figure 4) show the variability in space and time. The data was collected from four sources, with Strowan station being the most representative due to its proximity to the study area, located approximately 8 km away. The graph shows that there is no clear trend of rainfall, some years receive more rain than others. The annual rainfall amounts range from as low as 220 mm to as high as 1000 mm a year, with both CHIRPS (extracted for the Firglen study site) and Strowan having a mean annual rainfall of 650 mm.

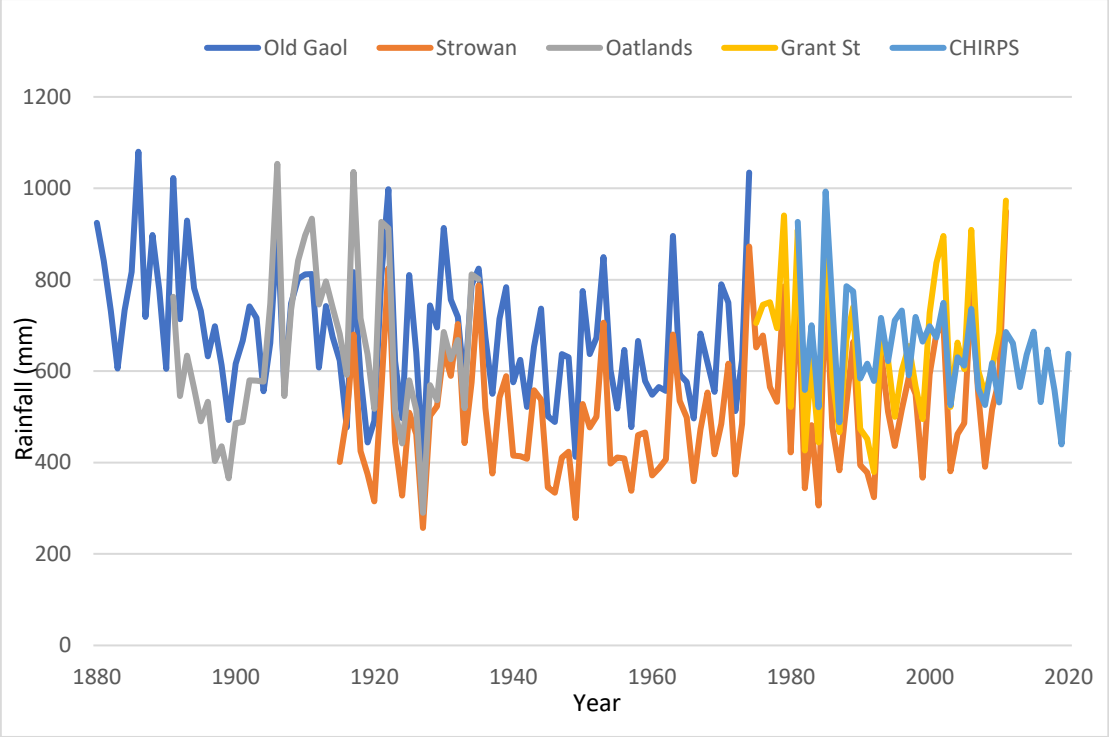

Figure 4: Historical mean annual rainfall (MAR) from four locations and the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) database in the Grahamstown area (Source: AR Palmer)

3.2.2 Vegetation

The Firglen study site is situated in the Subtropical Thicket Biome which is comprises of 14 vegetation units, including the Sundays Thicket, Coega Bontveld, Sundays Noorsveld, Great Fish Thicket, Kowie Thicket, Great Fish Noorsveld and Southern Mistbelt Forest (Hoare et al., 2006). The vegetation units that are found at Firglen include the Great Fish Thicket characterised by a diverse vegetation formation comprising of *Portulacaria afra, Gymnosporia, Schotia spp., Crassula spp., Euphorbia bothae,* and *Strelitzia reginae* and grasses such as *Eragrostis plana* (Hoare et al., 2006). The Southern Mistbelt Forest vegetation unit can be found in the south-facing high-altitude areas between 850m and 1600 m above sea level. This vegetation type is characterised by tall and short trees, *Afrocarpus falcatus, Celtis africana* and *Olea capensis* can be found in this vegetation unit (Hoare et al., 2006). The study area is contains numerous game and other species, including baboons (*Papio ursinus*), leopards (*Panthera pardus pardus*), kudu (*Tragelaphus strepsiceros*). Firglen farm has been invaded by several invasive alien plants, including species of the genera *Pinus, Eucalyptus* and *Acacia.*

3.2.3 Geology

The geology of the study site is characterised by the occurrence of rocks from both the Cape Supergroup and Karoo Supergroup (Buttner et al., 2015). The Cape Supergroup was deposited during the Ordovician era about 500 million years ago (Evans, 1998). It stretches from the Western Cape to the Eastern Cape Province of South Africa (Lock, 1974; Buttner et al., 2015). The rock formations at Firglen belong to both the Witteberg and Bokkeveld Group of the Cape Supergroup (Lock, 1974). Most of the Bokkeveld rock formations are found towards the town of Alexandria, with only a few outcrops around the Makhanda area (Buttner et al., 2015). Grahamstown region is dominated by rocks of the Witteberg Group (Lock, 1974). The Witteberg Group was deposited in a coastal marine setting during the mid-Devonian to mid-Carboniferous era and it is characterised by the occurrence of quartzite with interbedded shales (Buttner et al., 2015). The Witteberg Group is overlain by the glacial deposits of the Dwyka Group of the Karoo Supergroup (Lock, 1974). The Dwyka tillite is in turn overlain by the Ecca Group. These two groups are only exposed in the north east of Grahamstown (Lock, 1974). The Dwyka Group is dominated by glacial till while the Ecca Group is dominated by sandstone and shales (Buttner et al., 2015).

3.2.4 Land use

Historically the Makhanda area and Firglen was occupied by Xhosa pastoralists and San hunter gatherers for centuries who used this area primarily for grazing their cattle and hunting until the arrival of European settlers in the 1820s (SAHO, 2023). The arrival of Europeans changed the way the land was utilised since the Europeans came with new farming methods (Foster et al., 2012; Hamann and Tuinder, 2012; SAHO, 2023). The largely dense thicket was cleared to make way for cultivation and grazing for cattle (SAHO, 2023). Firglen has been cultivated for decades but cultivation has since ceased in the area. According to a local farmer Mr A. Du Preez (personal communication, 2023) the area was cultivated with tomatoes and flowers and small stock farming was practiced evidenced by the occurrence of water troughs. The cultivation practices of the past have left the soils at Firglen nutrient deficient and acidic despite the fact that the area has not been cultivated in over 50 years. The predominant land use today is grazing for Nguni cattle for a few months of the year. The farmer practices rotational grazing in order to curb overgrazing and avoid issues such as biodiversity decline, reduced biomass and land degradation (Du Preez, personal communication, 2023).

3.3 Cultivation framework and experimental design and layout Firglen

3.3.1 Germination

Germination was undertaken using landrace seeds which had been acquired from a local community of legacy growers. Phase one commenced on the 10th of September 2022. The seeds were germinated on 25 by 51 cm trays with cell size of 2.5 by 2.5 cm for approximately four weeks. The seeds were immersed or soaked in different jars of water for 24 hours, the seeds had to sink to the bottom of each container. After 24 hours the seeds were placed between a double folded paper towel, damp and cover with cling wrap. Phase two involved germinating the seeds that have roots in trays that were filled with a mixture of locally-prepared cannabis soil mixture, potting soil, powder feeding and vermiculite (magnesium-aluminium-iron silicate). Vermiculite has properties that allow it to absorb significant amount of water and attract other minerals that are essential for plant growth such as potassium (Gardeners Worldwide,2022). The seeds were planted in trays to a depth of about two centimetres (Figure 5). In phase three, upon completion of germination, a total of 450 *C. sativa* seedlings emerged, with a distance between them on the trays of approximately 20 cm. The seedlings were watered twice a day in the morning and afternoon for a few minutes, the seedlings were watered until the soil was evenly moist and not saturated using a hose pipe connected to a tap near the nursery facility at Firglen (Figure 5).

Figure 5: Plants in germination trays on the 2nd of September 2022 and in growing bags on the 20th of October 2022 in Firglen.

3.3.2 Transplanting

On October 7th, 2022, when the seedlings reached heights ranging from 15 to 20 cm and were 27 days old, they underwent transplantation into black 2-liter polyethylene bags for hardening. The bags were filled with the same mixture as the one used for germination. When the seedlings reached about 35 cm in height, on the 3rd of November 2022 they were planted in the cropping area.

Fourteen days before transplanting to the cropping area, all existing plants (mainly the grass *E. plana*) were treated individually with a 1% solution of glyphosate to ensure there was no competition during the growing season. The transplanting process was carried out by a team of five individuals. A bucket-type soil auger was used to dig 10 cm deep holes. A total of 450 seedlings were transplanted into the cropping area. The spacing between the plants was approximately 1 metre. An emergency drip irrigation system with a spacing of 1 metre between the drip holes, delivering 1 l $hour^{-1}$ plant, was installed to provide the opportunity to water plants only during extreme dry periods when soil moisture fell below 20%. When these conditions occurred, the moisture below plants were watered twice a day for about two hours each using the drip irrigation system, delivering 2 l day^{-1}. Consentino et al. (2012) recommends 450 ml (0.45 l) of water for *C. sativa* growing semi-arid areas. The plants were planted adjacent to the outlet of plastic drip irrigation pipes with holes. A seedling was planted adjacent to a drip hole in the dripline (Figure 6).

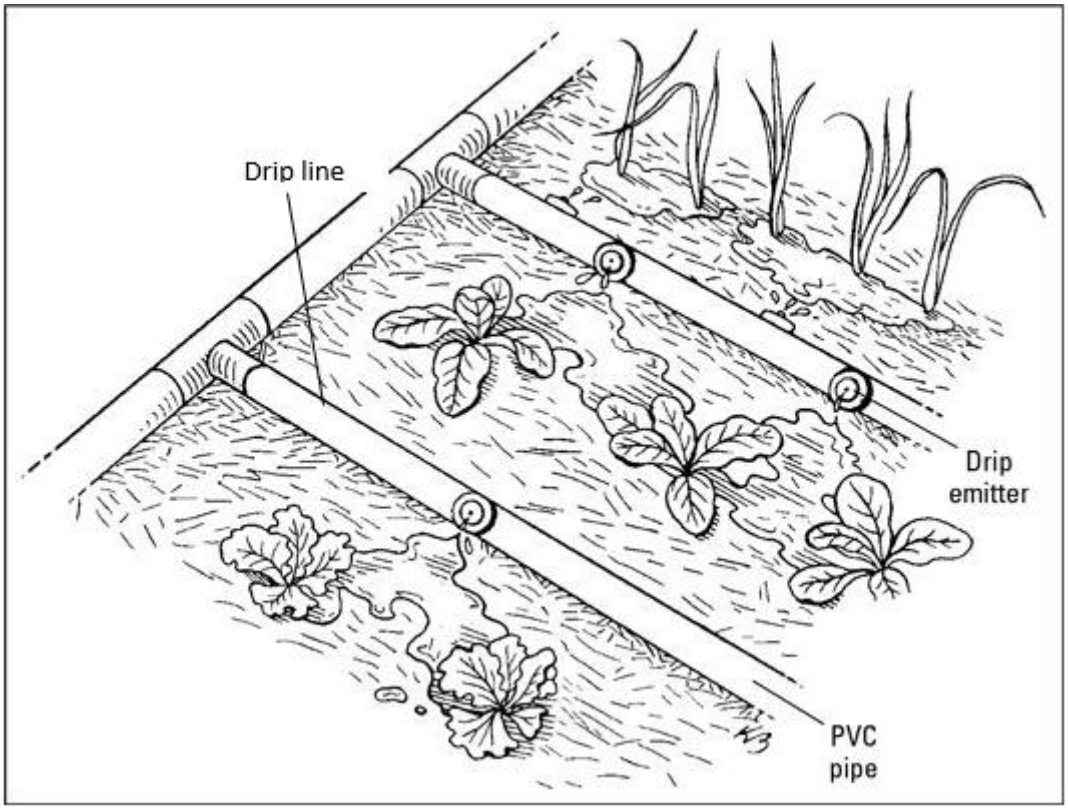

Figure 6: An example of drip irrigation, together with its components such as drip line, drip emitter and pvc pipe (Taken from watering systems for your vegetable garden, 2024).

The entire study area was protected from livestock with a high impedance electric fence (Figure 7).

Figure 7: Cannabis sativa during different growing stages, the image on the left shows seedlings that are ready to be transferred to the field and the second image shows a fully-grown plant in the field.

3.3.3 Biophysical monitoring

The main aim of biophysical monitoring at the Firglen study site was to monitor the progress of the plants throughout the growing cycle. This included monitoring the LAI, height and width of the plant and stomatal conductance (g_s). In addition, during the 2021-22 growth season, the same biophysical parameters of the local grass *E. plana* were measured to provide the background parameters for evapotranspiration modelling. The length of time the *C. sativa* plants were irrigated was recorded. There was no supplementary irrigation provided to *E. plana* in the 2021-22 season.

3.4 Instruments

Water use was determined by one form of direct measurement, and mechanistic modelling using an independent set of micro-meteorlogical data. The direct method was scintillometry, while the modelling required the measurement of biophysical parameters and the collection of high precision micro-meteorological data. The biophysical data obtained from the leaf porometer, namely the leaf-level stomatal conductance (g_s), and meteorological data were used in the MEDRUSH model to predict ET. MEDRUSH was developed by Osborne & Woodward (1999) of the University of Sheffield, United Kingdom and has undergone various developments in order to adapt it to different climatic regions.Plant physiological parameters such as height, width and leaf area index (LAI) were measured as indicators of productivity and health.

3.4.1 Large Aperture Scintillometer (LAS)

The Large Aperture Scintillometer (LAS MkII, Kipp & Zonen, 2022) was installed on the study site at Firglen on the 1st of October 2021. The LAS measures the refractive index of air (C_n^2) over horizontal path lengths from 250 m to 4.5 km and has a 0.149 m diameter (D) beam (Campbell Scientific, 2021). This instrument uses the principle of scintillation in order to obtain measurements (Hemakumara et al., 2003). Refractive index fluctuations are due to distortion of a wave traveling through air (Hemakumara et al., 2003). Hemakumara et al. (2003) describes scintillation as changes in the brightness of an object when viewed in the earth's atmosphere. The measured refractive index fluctuations are used to determine sensible heat flux. The fluctuations in the air are caused by the evaporating water, this occurs because water vapour in the air humidity and moisture content of the air. Higher humidity levels lead to denser air, which in turn affects the refractive index (Hemakumara et al., 2003). LAS consists of a transmitter and receiver which are situated on opposite ends of the study area. The beamlight transmitted by the LAS MkII transmitter emits a light that is near infrared at wavelength of 850 nm (Palmer et al., 2022).

The data logger for the LAS MkII is a CR3000 (Campbell Scientific) with an operating temperature between 20˚C and 60˚C (LAS MkII, Kipp & Zonen, 2022). The data collected by the LAS (scaled C_n^2(m-2/3), standard deviation of scaled C_n^2 (m-2/3), demodulated signal strength (V), standard deviation of demodulated signal (V)) and all the data from the ancillary micro-meteorological sensors and probes (radiation, wind speed and direction, air temperature, relative humidity, soil heat flux, soil temperature and soil moisture) are logged every 20 minutes by the programme in the CR3000. These data are downloaded from the logger and prepared for use in the Evation software (LAS MkII, Kipp & Zonen, 2022) in order to compute sensible heat flux over the crop. Evation can also generate graphs

that depict the interaction between ET, radiation and relative humidity. A modem at the site allowed LAS and the micro meteorological data to be accessed remotely.

The LAS was installed at the site as per instructions provided by Kipp-Zonnen (2021). The effective height of the LAS at Firglen was 1.83 m. The location of the path length (beam) and the underlying surface topography at the study site is presented (Figure 8).

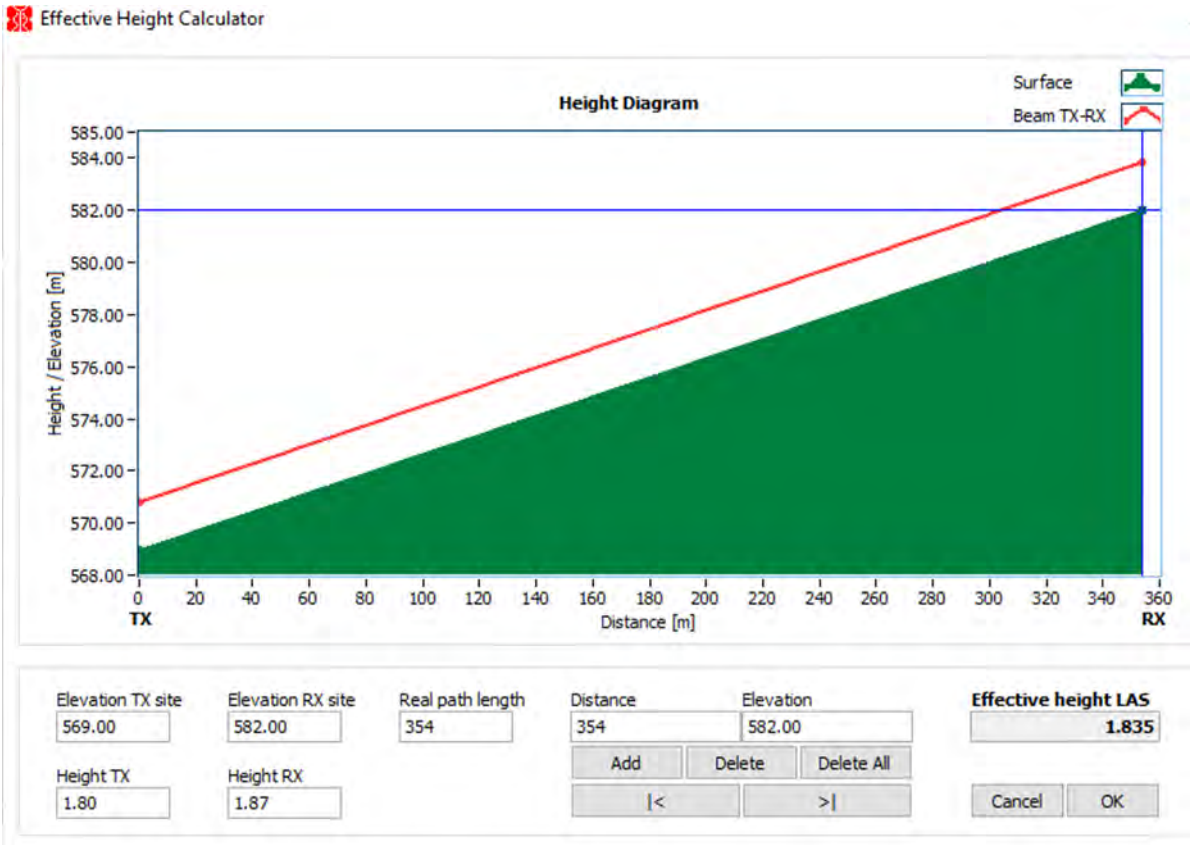

Figure 8: Path length beam and underlying surface topography between the Large Aperture Scintillometer (LAS) transmitter (TX) and receiver (RX) at Firglen (Evation software LAS MkII, 2023).

The distance between the transmitters and the receiver was 354 m, the elevation at the transmitter was 569 m while the elevation at the receiver was 582 m, giving an effective LAS height of 1.835m.

3.4.2 Micro-meteorological/weather station

The station measures net radiation (R_n), wind speed and direction, soil heat flux (G), volumetric soil water content (SWC), air and soil temperature (Ta and Ts) as well as relative humidity (RH). Micro-meteorological variables and instruments used are presented (Table 1). Two net radiometers (NRLite, Kipp & Zonen, Delft, The Netherlands) are used to measure R_n at 2 m above the canopy. The G was measured using four soil heat flux plates (HFP01, Campbell Scientific Inc., Logan, Utah, USA). The plates were placed at a depth of 80 mm below the soil surface. A system of parallel soil thermocouple probes (TCAV, Campbell Scientific Inc., Logan, Utah, USA, 2022) were installed at depths of 20 and 60

mm to measure soil temperature above the heat flux plates. A soil thermocouple probe measures temperature at four locations, or junctions, each consisting of type E thermocouple wire (chromel-constantan) that is enclosed within a stainless-steel tube (Campbell Scientific, 2022). It operates in conjunction with the soil heat flux plate to calculate the heat flux at the surface of the soil. Volumetric soil water content (CS616, Campbell Scientific Inc., Logan, Utah, USA, 2022) is measured in the upper 60 mm of soil using two sensors. The installation of heat flux plates, soil temperature thermocouples and the water content reflectometer were done following Campbell Scientific (2002). An HC2S3 probe (Campbell Scientific Inc., Logan, Utah, USA, 2022) was used to measure air temperature and relative humidity. This sensor is appropriate for long-term, unattended applications. Air temperature was measured using two unshielded type-E (chromel/constantan) fine-wire thermocouples (FW05, Campbell Scientific Inc., Logan, Utah, USA, 2022) placed at heights of 1 m and 2.7 m above the ground surface. The FW05 is a fast response Type E thermocouple with a 0.012 mm in diameter. It measures atmospheric temperature gradients or fluctuations with research-grade accuracy. Wind speed and direction were measured using an anemometer (Wind Monitor-AQ, model 05305, R.M. Young Company, Michigan, USA, 2022) locate at 2.5 m above the surface (Figure 9).

Table 1: List of instruments at the Large Aperture Scintillometer (LAS) Micro-Meteorological Station

Bio-meteorological variable	Instrument
Soil heat flux (W.m^{-2})	4 x soil heat plate (HFP01), (Hukseflux Thermal Sensors, Delft, Netherlands)
Volumetric water content (%)	Water content reflectometer (CS616, Campbell Scientific Inc., Logan, Utah, USA)
Temperature and RH (%)	HC2S3 Temperature and RH Probe (Campbell Scientific Inc., Logan, Utah, USA)
Soil temperature (°C)	2 x Averaging soil thermocouples probe (TCAV, Campbell Scientific Inc., Logan, Utah, USA)
Net radiation (W.m^{-2})	2 x net radiometers (NR-lite2) (Kipp and Zonen, Netherlands)
Air temperature (°C)	2 x fine wire thermocouples (FW05: 0.0005 inch /0.0127 mm, Campbell Scientific Inc., Logan, Utah, USA) at 1.0m and 2.5m above soil surface
Wind speed (m.s^{-1}) and direction (degrees)	Wind Monitor-AQ, model 05305, R.M. Young Company, Michigan, USA

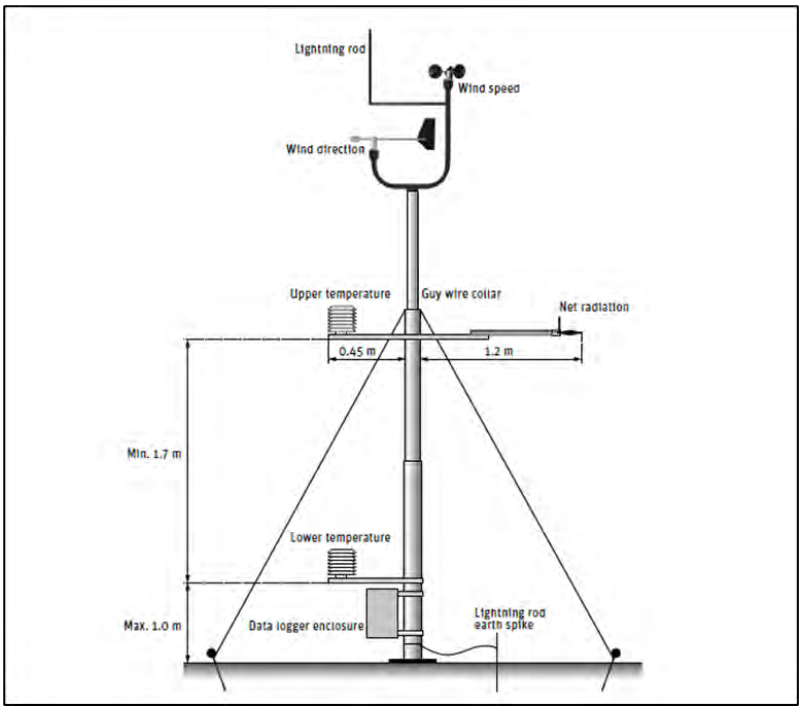

Figure 9: Illustrates a sketch of the weather station at Firglen study site (LAS MkII, Kipp & Zonen, 2022).

Due to the high spatial variability in rainfall (Figure 14) additional precipitation data was obtained from local and remotely sensed sources. The Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) provided gridded precipitation estimates at a high spatial resolution of approximately

0.05 degrees (approximately 5 km) for the duration of the project. CHIRPS is a global rainfall dataset system that integrates data from real-time meteorological stations with remotely sensed infrared data from multiple sources such as the United States National Oceanic and Atmospheric Administration (NOAA) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) (Water resources associates, 2024; Funk et al., 2016).

Local measurements were also taken during the growing seasons using two standard plastic rain gauges, one on Firglen and one in a neighbouring farm "Ed Farm". Both gauges were positioned in open areas away from obstructions such as trees to ensure accurate readings. Data collection involved regularly checking the rain gauge and recording the accumulated precipitation. CHIRPS daily data provided a more consistent record than the manual gauges for modelling purposes as it recorded rainfall during all the 24 hour day/night cycles of the growth period.

3.4.3 Leaf porometer

A hand-held SC-1 model leaf porometer (Decagon Instruments, USA) is used to measure stomatal conductance (g_s) from the leaf of a *C. sativa* plant. This measurement provides information about the difference between transpiring leaves and leaves that have closed their stomata (MeterGroup, 2022). The stomata are the openings or pores found on the epidermis of leaves, stems and other plant organs, and they are primarily responsible for the gaseous exchange whereby water vapour exits the plant in a process known as evapotranspiration and carbon dioxide is taken in (Esau, 1977). The CO_2 is a vital component of the process of photosynthesis which is one of the most important processes on earth (Swarthout and Hogan, 2010). This process is responsible for converting radiation or light energy into chemical energy that is utilised by plants and other organisms for survival i.e., used as fuel (Swarthout and Hogan, 2010). Stomatal conductance is defined as the rate at which CO_2 enters or H_2O exits through the stomata of the plant (Thomas et al., 2017). Stomatal conductance is controlled by degree of stomatal opening (Gimenez et al., 2005), and measures the rate of gaseous exchange between the atmosphere and the leaf of a plant.

The SC-1 leaf porometer has a sensor head that is sensitive to relative humidity changes (Thomas et al., 2017). The porometer chamber is clamped carefully over the leaf in a single movement, ensuring that the leaf is not excessively disturbed prior to the sensor head being in place. Each reading takes approximately 30 seconds when the leaf porometer is automated, and the stomatal conductance is expressed in units of ummol $m^{-2}s^{-1}$.

A random systematic sampling grid was developed on Microsoft excel. This enables the random selection of plants ensures no repeats and removes any biases that might be introduced. Twenty-five

plants at the Firglen study site were sampled on a sunny cloudless day and the data received was stored in the SC-1 leaf porometer and later captured on an excel spreadsheet, the data is recorded on a book in case the one stored in the leaf porometer is corrupted or lost.

3.4.4 Leaf Area Index

A hand-held Accupar ceptometer (MeterGroup, 2022) was used to measure the Leaf Area Index (LAI) of *C. sativa* plants. Leaf Area Index is a critical parameter in plant science and ecology that quantifies the extent of leaf area per unit of ground area (Fang et al., 2019). It is a measure of the density and coverage of plant canopies and plays a crucial role in understanding various ecological processes, such as photosynthesis, transpiration, and overall ecosystem productivity (Breda, 2003; Fang et al., 2019). LAI is calculated by dividing the total leaf area by the ground area it covers (Breda, 2003). This index provides valuable information about the vegetation structure, helps in assessing the health and vitality of plant communities, and aids in monitoring changes in ecosystems over time (Breda, 2003).

3.4.5 Plant height and canopy

The height of a plant is defined as the vertical distance from the base of the plant's stem or root system to the highest point of the plant's structure (Pérez-Harguindeguy et al., 2016). Height measurements were conducted using a standard measuring tape, with reference taken from the base of the main stem at soil level. To ensure precision, the measuring tape was positioned vertically, perpendicular to the ground. Three height measurements were obtained for each plant, and their average was computed for enhanced accuracy. All measurements were recorded in metres. Plants were maintained upright, with support for main stems if needed to prevent bending or leaning during measurement sessions. Height measurements were taken twice a month during the growing cycle.

Plant canopy width refers to the horizontal extent or spread of a plant's foliage or branches when viewed from above (Pérez-Harguindeguy et al., 2016). In this study plant width was measured by laying a measuring tape horizontally across the widest part of the plant canopy when viewed from above. Each measurement was taken from the outer edge of one side of the canopy to the outer edge of the opposite side, ensuring the tape was aligned perpendicular to the ground for accuracy. Three measurements were taken just as in height measurements.

3.5. MEDRUSH

MEDRUSH offers a portrayal of water and energy movement within an ecosystem. Meteorological and stomatal conductance measurements drive the model, enabling the simulation of fluxes across a crop or a specific land area. The model was developed by Osborne and Woodward of the University of

Sheffield, United Kingdom, and presented at the BBSRC-funded workshop entitled "Ecophysiology Techniques Workshop" in Lisbon, Portugal from 10-15th September 2012. MEDRUSH uses an equation from Buck (1981), reproduced by Jones (2014) to calculate saturation vapour pressure from air temperature.

Equation for saturation vapour pressure *P*sat=*A*−*T/B*

Stomatal conductance (g_s), a required input into the model, needs to be provided under a range of growing conditions for cultivation Equation for Gs is $G_s=K_{soil}\left|g_0 + g_1P_a10^{-6}A_1/(C_a\text{-}r)\right.(1+ \delta e_a/g_2)$.

- *Gs*: Stomatal conductance
- Ksoil*K*soil: Soil water availability factor
- $g0$: Minimum stomatal conductance
- $g1$: Sensitivity of stomatal conductance to atmospheric vapor pressure deficit (Pa
- Pa: Atmospheric vapor pressure deficit.
- A: Leaf area
- *Ca*: Ambient CO_2 concentration, the concentration of carbon dioxide in the air surrounding the plant.
- gg: Stomatal conductance to CO_2
- rr: Stomatal conductance to water vapor
- $\delta\delta$: Slope of the relationship between leaf internal CO_2 concentration and stomatal conductance.
- *ea*: Ambient vapor pressure
- $g2$: Slope of the relationship between stomatal conductance and ambient vapor pressure

The model uses the micro-meteorological data and the stomatal conductance to compute energy fluxes. The main inputs to the MEDRUSH model include: (a) physical site-specific parameters, (b) ecosystem specific parameters and (c) meteorological data. The meteorological data used by MEDRUSH were obtained from the micro-meteorological sensors and probes at 20min intervals, and include minimum and maximum air temperature, relative humidity, soil temperature, wind speed and solar radiation. All data were obtained from the weather station at the site. MEDRUSH is written in R programming language (R Core Team, 2023). For this work MEDRUSH scripts were run using R (version 4.3.3) and RStudio (version 2023.12.1+402; RStudio Team, 2023))

This model was selected because it requires only a few inputs to predict evapotranspiration (ET), such as meteorological parameters and stomatal conductance. This feature makes it particularly useful in remote areas and where financial constraints are prevalent.

3.6 Parameterization and Validation

For model parameterization the inputs are the meteorological parameters and porometry data throughout the growth period of *C. sativa*. This data serves as inputs for implementing the MEDRUSH evapotranspiration model using an R script.

The continuous measurements of evapotranspiration from the LAS taken throughout the growth period of *C. sativa* are used for model validation. The goodness-of-fit of the model is evaluated using root mean square error (RMSE), mean absolute error (MAE), Ratio of RMSE to the Standard Deviation of the Observations (RSR), percent bias (PBIAS) and coefficient of determination (R^2). Furthermore, the model's performance is assessed at stages of crop growth to comprehensively understand its behaviour.

3.7 Statistical analysis

Statistical analyses, including correlation coefficients and regression analyses, were conducted to evaluate the relationship between evapotranspiration estimates obtained from the MEDRUSH model and those derived from the LAS system. The monthly means for plant biophysical parameters (stomatal conductance, height, canopy width and LAI) were compared using the Kruskal-Wallis test, followed by subsequent pairwise comparisons utilizing Wilcoxon's test to discern significant differences between specific groups.

Analysis was conducted in R (R Core Team, 2023) using the base R functions using RStudio (version 2023.12.1+402; RStudio Team, 2023). Data manipulation was done with the dplyr package (Wickham et al., 2023) and data visualisation was done using the ggplot2 package (Wickham, 2016).

3.7.1 Data Quality control

Throughout the data analysis stage, the LAS data underwent various quality checks. These checks included:

1. Removing positive fluxes occurring between sunset and sunrise with a friction velocity (u*) less than 0.1 $m \cdot s^{-1}$. This was done to avoid conditions with poorly developed turbulence due to low wind speeds.

2. Daytime fluxes were utilised, between 7:00 and 16:00. This was done because most of the turbulence or unstable conditions occur during the day i.e., elevated temperatures, relative humidity and other measured meteorological parameters.
3. Filtering out periods featuring a temperature gradient of less than 0.2°C between the lower and upper air temperature sensors to mitigate the risk of inaccuracies in determining atmospheric stability.
4. The Bowen ratio (β) was employed as a criterion for eliminating positive fluxes, particularly when it surpassed three. During such instances, the sensible heat (H) significantly outweighed the latent heat (LE), rendering the latter negligible. Data points featuring a β within the range of -0.05 to 0 were excluded due to the inherent instability of the solution within this extreme value range, in accordance with the recommendations of Rambikur and Chávez (2014). It is important to note that over wet surfaces, β tends to be small (<0.5), and when β exceeds 3, LE becomes insignificant (Bouin et al., 2012; Kipp and Zonen, 2012). Additionally, periods with β in close proximity to -1 (i.e., $-1.25 < \beta < -0.75$) were taken into consideration, during which LE and H were assumed to be negligible, (Campbell Scientific,2022).

The data quality control also included filtering out data with a low signal (demodulated signal less than 10 Mv), as stipulated by EVATION software requirements.

Chapter 4. Results

4.1 Meteorological attributes of Firglen study site

The micro-meteorological/weather station has measured various weather parameters which include wind speed, air temperature, relative humidity, air pressure, wind direction, soil temperature. All these parameters are plotted below. Table 2 also illustrates the summary of the weather conditions during the study period at Firglen.

The thermocouple that is situated at a lower position on the mast exhibits a higher temperature (mean± standard deviation: 16.63 ± 6.27) when compared to the upper thermocouple (15.86± 5.40). The mean air temperature recorded inside the radiation shield was higher than the mean air temperature of both the upper and the lower thermocouples.

Table 2: Summary of meteorological conditions during the study.

Descriptive statistics				
	Mean	Standard deviation	Max	Min
Thermocouple T (upper)(˚C)	15.86	5.40	38.86	0.77
Thermocouple T (lower) (˚C)	16.63	6.27	44.60	-0.05
AirT (˚C)	18.30	6.12	44.60	2.21
Relative humidity (%)	73.43	20.85	100	7.81
Atmospheric pressure (Pa)	96.23	10.60	100.30	NA
Wind speed (m sec^{-1})	2.025	1.94	14.39	0.00
Soil temperature (°C)	16.85	5.55	40.72	6.17
Soil moisture (%)	22.45	6.21	25.97	17.83
Soil heat flux (Watts m^{-2})	0.70	31.90	143.30	n/a
Net radiation (Watts m^{-2})	71.72	186.00	985.30	n/a

An example of the annual variation in T_{air} at Firglen is presented over a period of 12 months with an average of (18.30 ± 6.12) (Figure 10). The highest air temperatures were recorded in the month of January 2022, with the maximum at 38.8˚C. The lowest recorded temperature was -0.05˚C in August 2022. The highest temperatures were measured between the months of January and March while the lowest average temperatures were measured in between the months of April and August 2022.

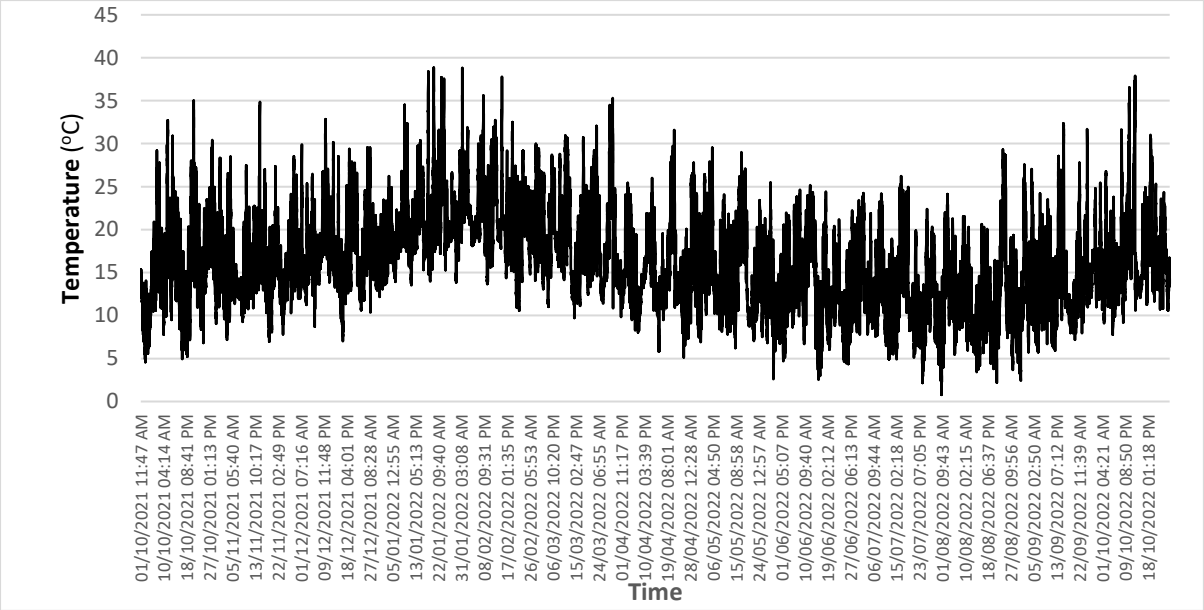

Figure 8: Air temperature (T_{air}) on Firglen during the first 12 months of the study.

An example of the variation in windspeed is presented over a comparable 12-month period. (Figure 11). The highest windspeeds were measured during the months of November and December 2021. This coincides with the cropping season for *C. sativa*. The highest windspeed measured was 14.39 m sec^{-1} in November 2021 and the mean windspeed was 2.03 ± 1.94.

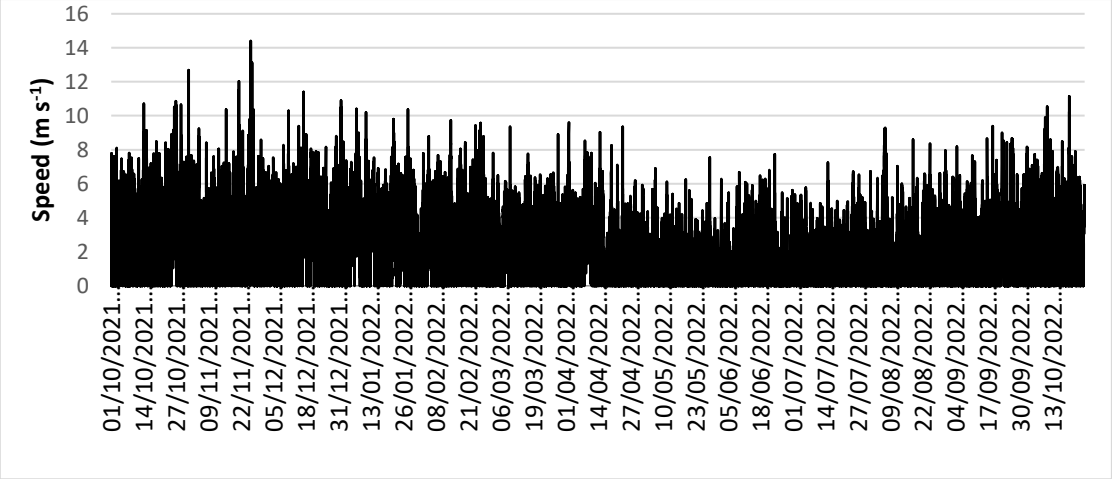

Figure 9: Maximum windspeed (m s^{-1}) on Firglen during 12 months of the study.

An example of the variation in soil moisture is presented over a comparable 12-month period. (Figure 12). The highest soil moisture was recorded between November and December 2021 and again between April and May 2022, while the lowest soil moisture was measured in the months of January and February 2022. The average soil moisture throughout the period was (16.85 ± 5.55).

The clear wet and dry season, and particularly the low soil moisture during April and May, indicates how important it is to be able to apply irrigation to maintain soil moisture throughout the growing season. Rapid decreases in soil moisture during the warm, wet season, linked to high evaporative demand, further support the need to be able to provide emergency irrigation under dryland conditions.

It was observed that plants were healthier (green and actively growing) when soil moisture was at 23% and above.

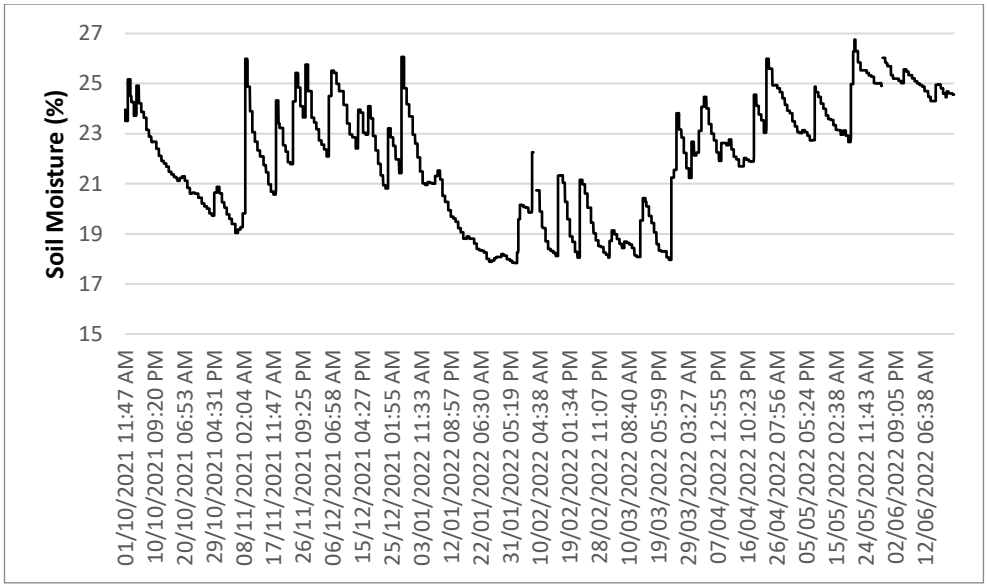

Figure 10: Soil moisture recorded throughout the study period.

The Firglen study site is situated in a valley and is therefore prone to katabatic winds also known as berg winds. These bergwind conditions occur in the summer season. This phenomenon has resulted in less-than-ideal conditions for the plants. It can be observed (Figure 13) that the occurrence of bergwinds which are associated with increased temperatures leads to lower soil moisture. The months of January and February (summer season) exhibited the highest air temperatures and the bergwinds were strongest during that period. It can be observed that the soil moisture decreases with increased occurrence of bergwinds.

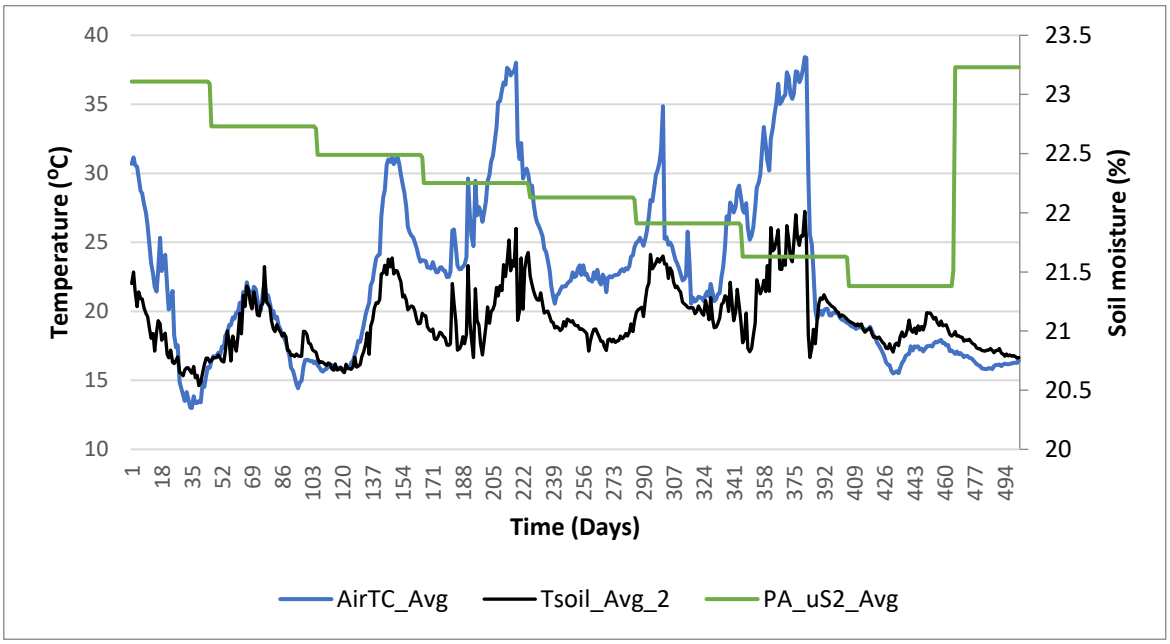

Figure 13: Bergwind conditions experienced at Firglen Study site. Periods of high air T (AirTC_Avg), high soil T (Tsoil_Avg_2) are accompanied by a decline in soil moisture (PA_uS2_Avg).

The rainfall data was collected in the growing cycle of *C. sativa* from November 2022 to February 2023 using rain gauge at Firglen. This was compared with data from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), a global rainfall dataset system that integrates data from real-time meteorological stations with infrared data to estimate precipitation. Total rainfall for the crop cycle from CHIRPS was 160 mm and that from the manual gauge at Firglen was 168 mm (Figure 14).

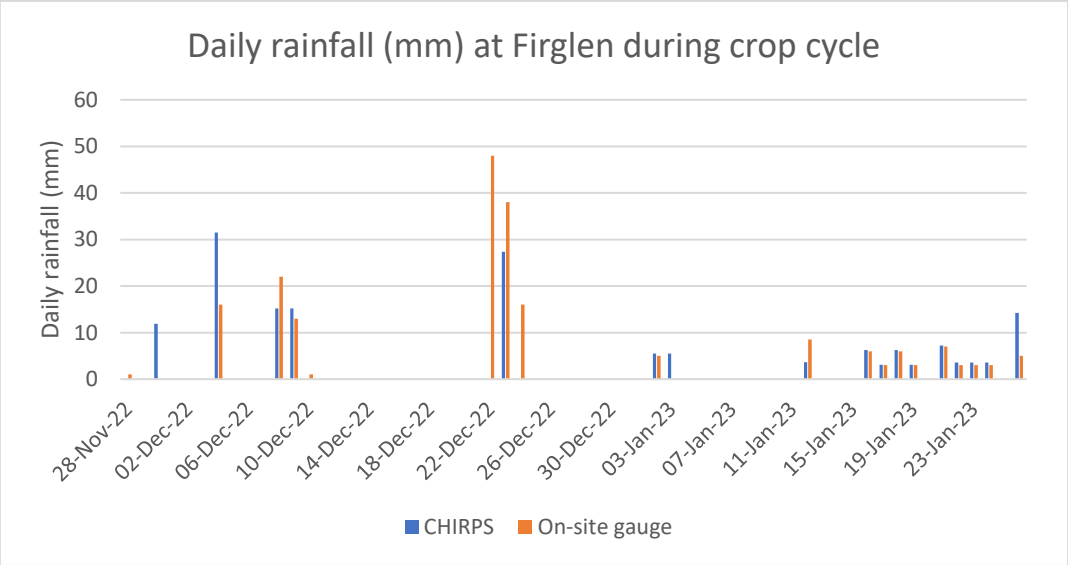

Figure 11: Daily rainfall from the on-site rain gauge and CHIRPS data for the Nov 2022-March 2023 LAS measurement.

Rainfall data for the Firglen study site spanning a period of almost two years from 2021 to 2023 was obtained from the CHIRPS model. The highest monthly precipitation (150 mm) was recorded in November 2021, while the lowest rainfall occurred in September of the same year, measuring 6.71 mm. (Figure 15).

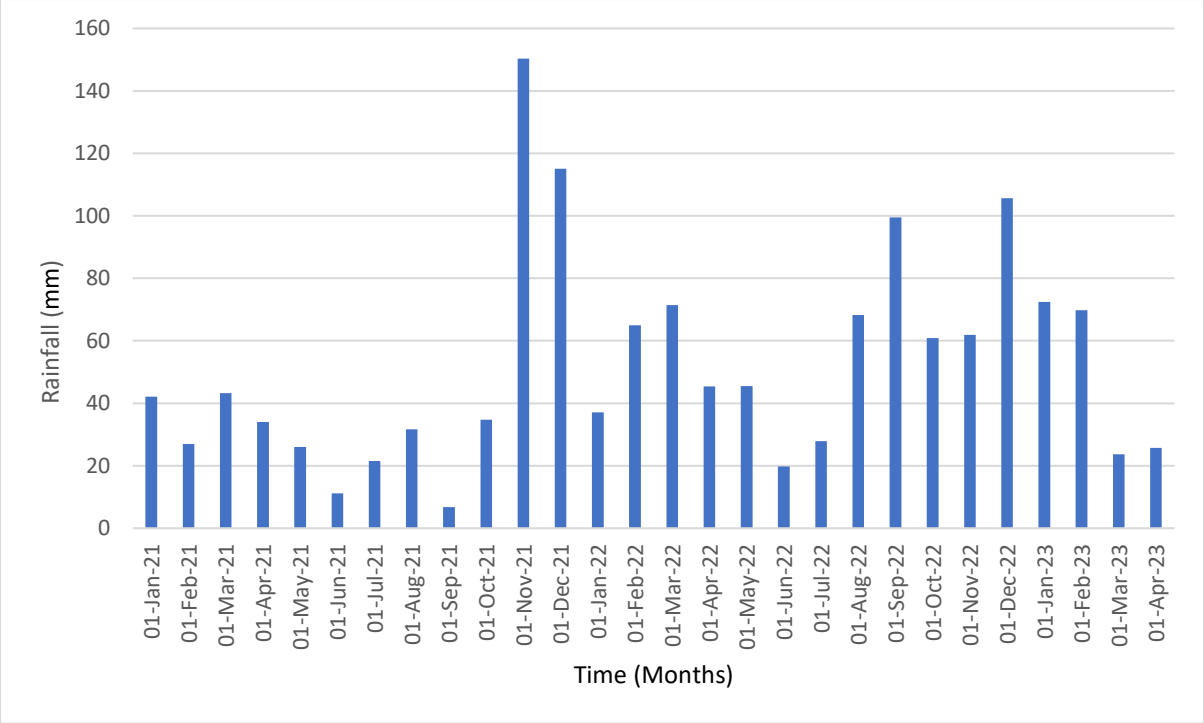

Figure 12: Monthly rainfall data for Firglen from 2021 to 2023 (source: CHIRPS).

The soil moisture data collected spans from October 2022, prior to the planting of *C. sativa*, through April 2023, post-planting. Analysis reveals significant variations in soil moisture content (%) throughout this period. Notably, December exhibited the highest soil moisture content, while April registered the lowest. Specifically, the 6th of January 2023 recorded the peak soil moisture content at 25.82%, whereas the lowest occurred on February 05, 2023. Additionally, a statistical analysis using analysis of variance (ANOVA) indicated a significant difference ($p < 0.05$) in soil moisture between the different months (Figure 16).

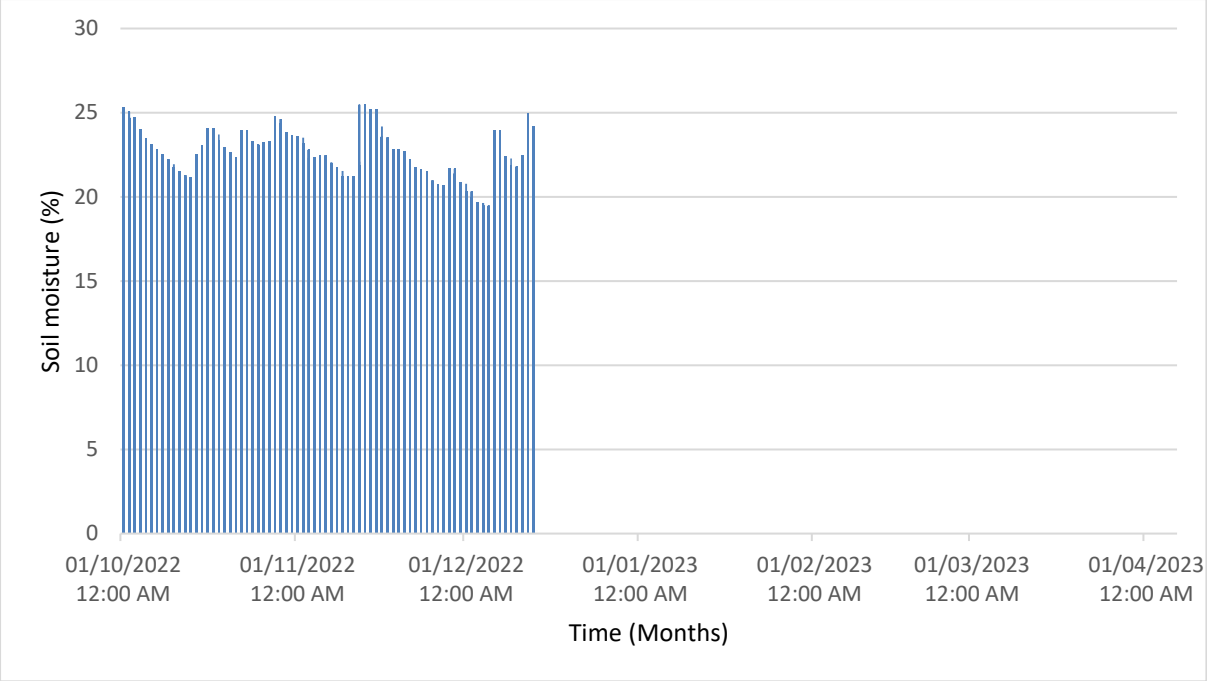

Figure 13: Soil moisture content during the second planting season from October 2022 to April 2023

During the study's second planting period, from early November 2022 to March 2023 when *C. sativa* was harvested, temperature measurements were conducted. The month of February 2023 exhibited the highest daily average temperature, recorded at 27.35±5.12 ˚C. Conversely, the lowest daily average temperature was observed in November 2022, measuring 20.28±5.14˚C. Additionally, the maximum temperature of 40.97 ˚C was recorded on the 1st of February 2023. These findings provide a comprehensive overview of the temperature variations observed throughout the specified planting season (Figure 17).

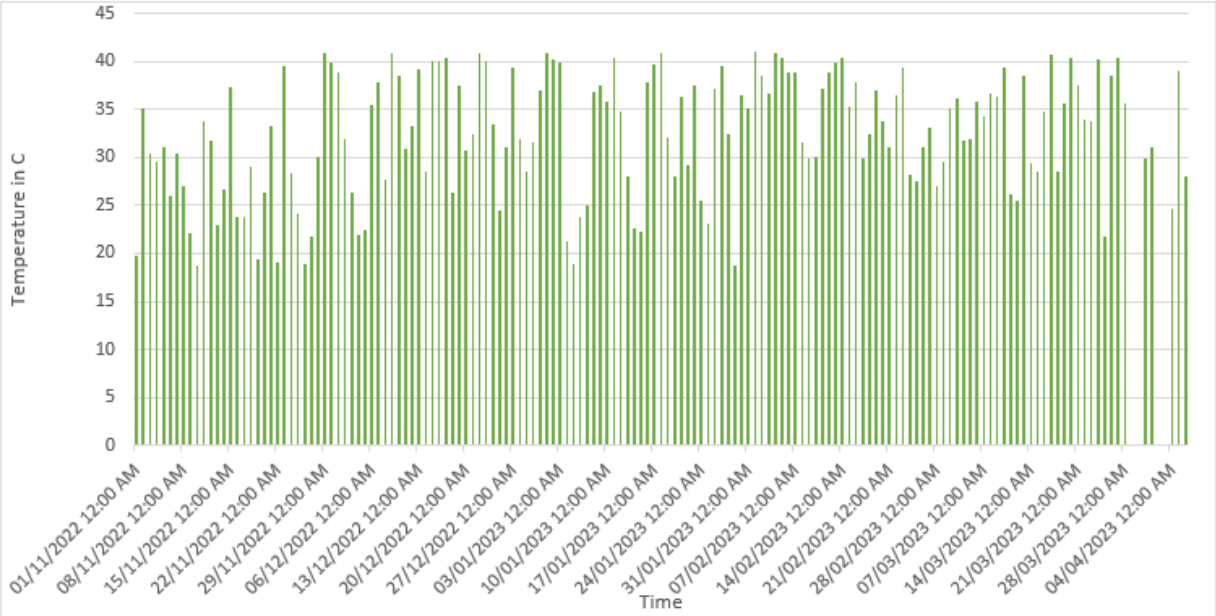

Figure 14: Daily maximum temperature measured over a period of six months at Firglen study site during the planting cycle beginning in November 2022

It was observed that the highest average wind speed occurred during the month of November 2022 at (2.73 ± 2.14 ms^{-1}) coinciding with the commencement of planting, while the lowest average wind speed was recorded in the month of April 2023 (1.20 ± 1.49 ms^{-1}). Additionally, the maximum daily wind speed was documented in February, reaching speeds of 12 ms^{-1} (Figure 18). It should be noted that after a high wind speed event (wind speeds above 4 m sec^{-1}) some plants exhibited signs of physical damage, such as broken branches.

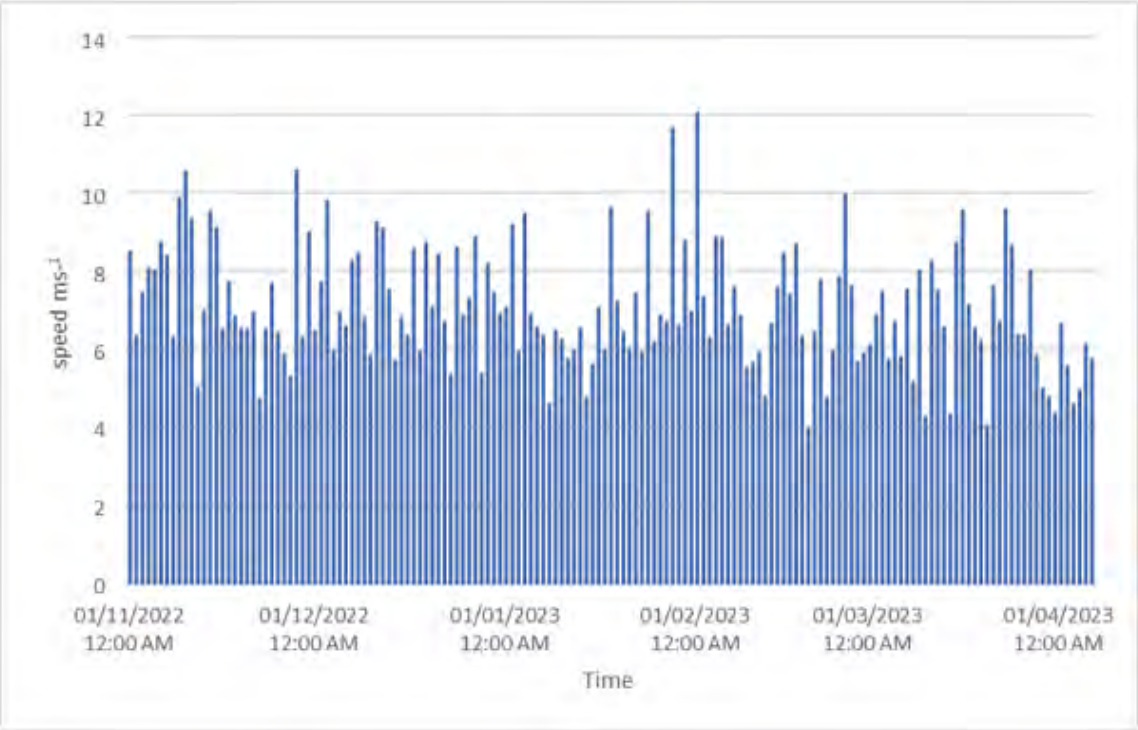

Figure 15: Wind speed measured at Firglen in the second planting season between the months of November 2022 and April 2023.

4.2 Comparative analysis of the ET of *E. plana* and *C. sativa* measured with a LAS

In our research, actual ET refers to the ET that is obtained from the Large Aperture Scintillometer (LAS), and hereafter actual ET refers to ET.

Figure 19 depicts the evapotranspiration (ET) of the indigenous grass species Eragrostis plana, measured prior to the planting of *C. sativa* in October 2022. This pre-planting assessment was conducted to establish the baseline ET the dominant vegetation cover before introducing *C. sativa*. By establishing this baseline, we ensure that subsequent measurements of ET of *C. sativa* are attributed only to *C. sativa*, rather than any residual influence from the grass. The data was measured using a LAS. The Figure indicates that the highest ET value occurred on October 1, 2022, reaching 0.93 mm.

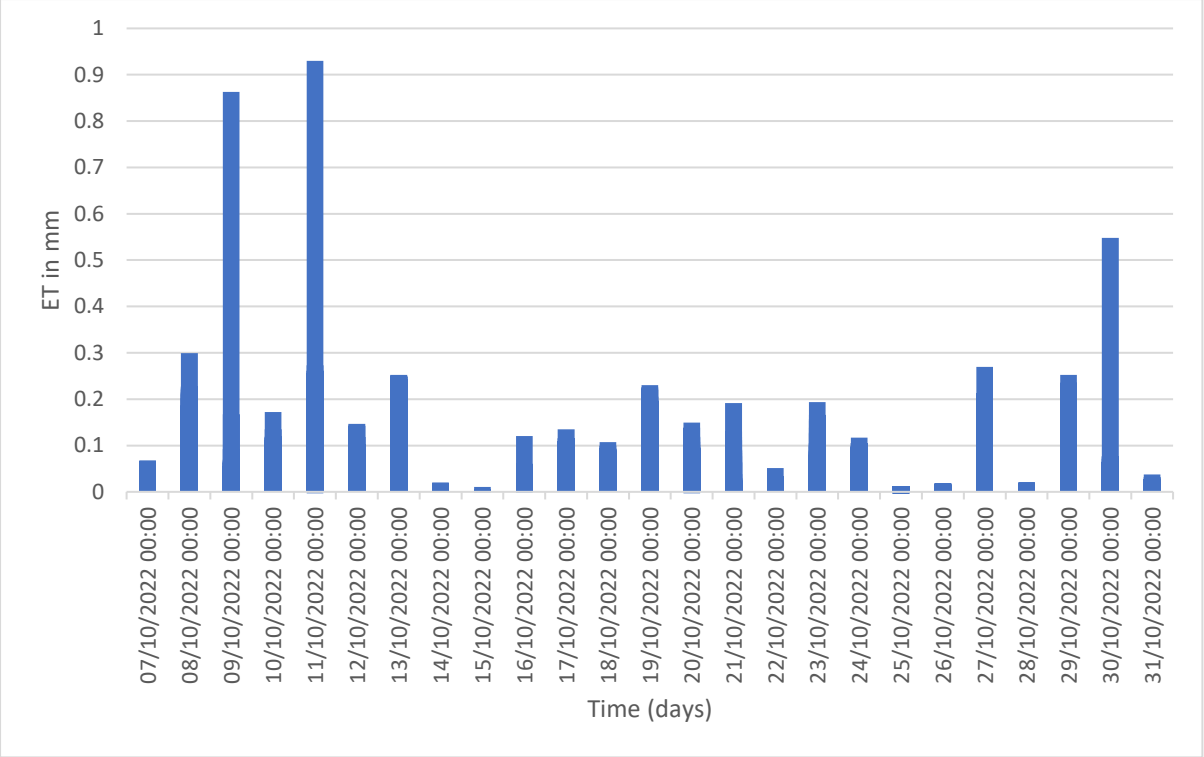

Figure 16: Evapotranspiration of Eragrostis plana in 2022

Figure 20 presents a graphical representation of the evapotranspiration rates observed in *C. sativa*. A total ET for *C. sativa* of 126.8 mm for November 2022 to January 2023 was measured, with a mean daily rate of 1.76 ± 0.84 mm (Figure 20). Notably, the 22nd of December 2022 recorded the maximum daily evapotranspiration rate, reaching a high of 4 mm. During this same period, the recorded total rainfall was 160 mm (CHIRPS) and 168 mm (on-site station).

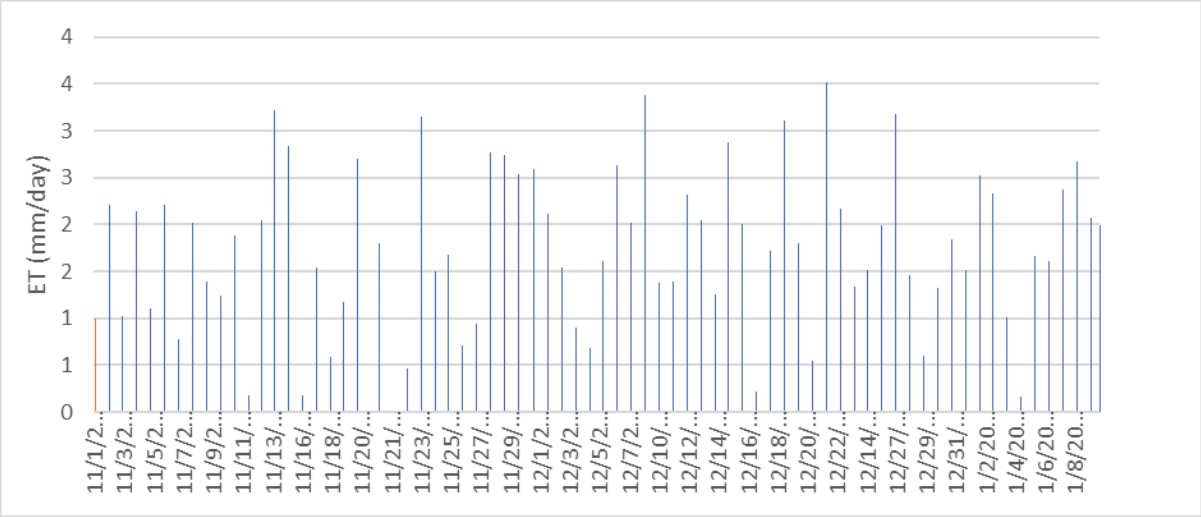

Figure 17: Daily Evapotranspiration of Cannabis sativa over a period of 72 days during the growing period from 1 November 2022 to 11h January 2023 as measured by the Large Aperture Scintillometer (LAS).

4.3 MEDRUSH

Table 3 presents a comparative analysis between MEDRUSH (g=10) and MEDRUSH (g=5), denoting distinct growth conditions for *C. sativa* and the indigenous grass species *Eragrostis plana*, respectively. The g denotes stomatal conductance. The experimental setup involved the planting of *C. sativa* in early February 2022 at Firglen, while the local grass at Firglen is *E. plana*. The results indicate that the daily modelled mean evapotranspiration (ET) is notably higher in MEDRUSH (g=10), representing *C. sativa*, at 2.52 mm, in contrast to MEDRUSH (g=5), which represents *E. plana*, where the mean ET is 0.63 mm.

MEDRUSH, the predictive model utilized for daily ET estimation, is evaluated against actual ET values obtained through the LAS at the Firglen study site. Comparative analysis reveals that MAE, RMSE, and RSR values for *C. sativa* are greater than those for *E. plana*, as outlined in Table 3. Furthermore, the percent for *C. sativa* exhibits a negative value, whereas that for *E. plana* is positive. Additionally, the daily ET values for *C. sativa* surpass those observed for *E. plana*.

Table 3: Model performance at Firglen illustrating the difference between Cannabis sativa (MEDRUSH g =10) and Eragrostis plana (MEDRUSH g= 5)

Descriptive statistics		
	MEDRUSH (g=10)	MEDRUSH (g=5)
MAE (mm)	0.113	0.077
RMSE (mm)	0.163	0.104
RSR	0.082	0.977
PBIAS (%)	-16.18	22.4
Daily modelled mean ET (mm)	2.52	0.63

4.4 Parameter estimation and validation at Firglen

The obtained R-squared value of 0.63 signifies a substantial explanatory power in the MEDRUSH model's (*C. sativa*) ability to predict actual measured ET. This metric indicates that approximately 63% of the observed variability in ET can be explained by the model's predictions. In the specific instance considered, the Large Aperture Scintillometer (LAS) recorded the actual ET as 1.76 mm, contrasting with the model's prediction of 2.52 mm. The regression equation expressed as y = 0.78x. For each incremental unit in the predicted ET (x-axis), the corresponding actual measured ET (y-axis) is anticipated to increase by a factor of 0.78. (Figure 21).

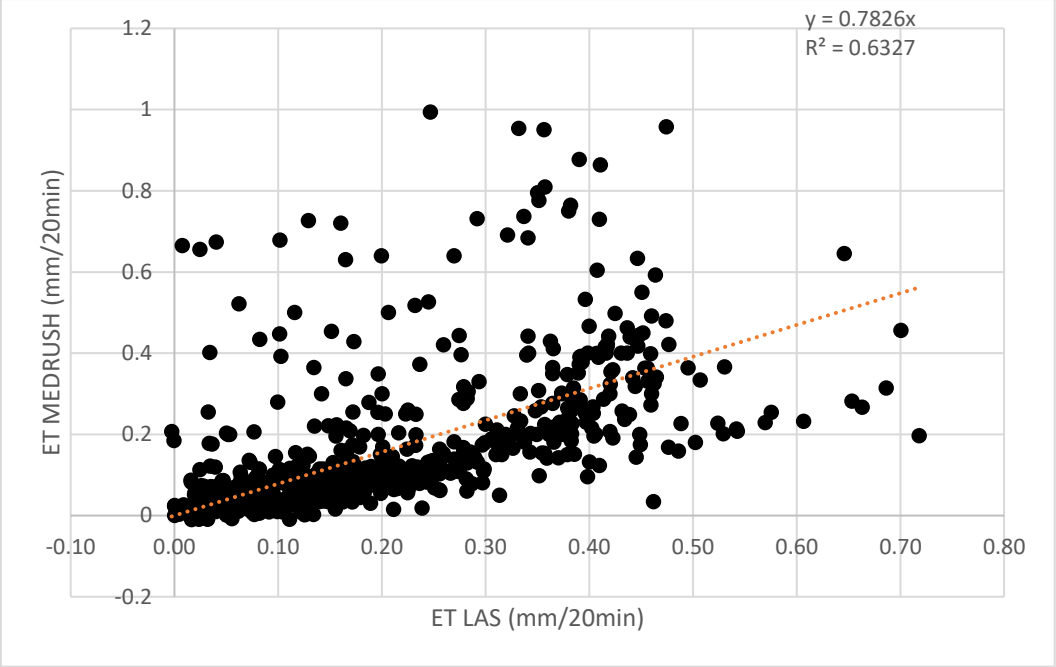

Figure 18: Comparison between MEDRUSH model and actual ET for C. sativa as measured by the LAS

The MEDRUSH (*E. plana*) was able to follow the dynamics of ET measured by the LAS at Firglen although its correlation is slightly less than the *C. sativa* one (Figure 22). This metric indicates that approximately 62% of the observed variability in ET can be explained by the model's predictions (Figure 22).

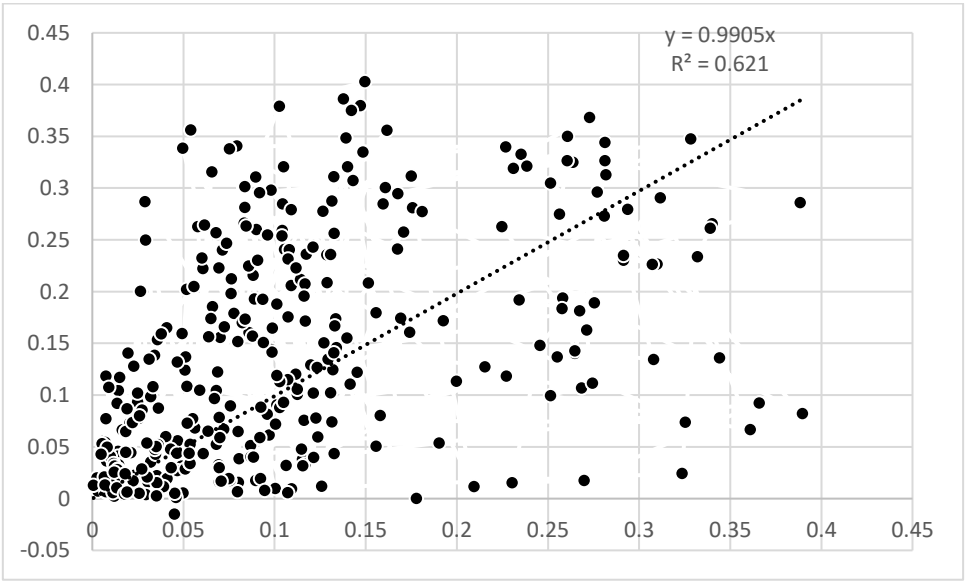

Figure 19: A correlation between the ET predicted using MEDRUSH (g_s=5) and actual ET of E. plana measured using the LAS.

Three different days were selected in December during the peak growing season to demonstrate some of the strengths and weaknesses of MEDRUSH. The selection of these days was deliberate, the main

aim was to showcase instances when the MEDRUSH model exhibited strong, moderate, and weak performance. This selection strategy aids greatly in the evaluation of the model's strengths and limitations. By presenting a spectrum of performance scenarios, this approach provides valuable insights for researchers, enhancing their understanding of the reliability and robustness of the MEDRUSH model in predicting evapotranspiration.

The MEDRUSH model and LAS of the 23rd of December followed a similar trend to the one observed in the overall comparison between LAS and MEDRUSH. On this day, the MEDRUSH model had the best estimation of LAS ET (Figure 23). Although MEDRUSH underestimates the daily ET, for example the highest LAS ET was 0.5 mm while the Highest MEDRUSH was 0.38 mm. This trend of underestimation has been observed on other days as well. Despite this underestimation, it is noteworthy that the MEDRUSH model closely aligns with the overall trend of LAS, indicating a positive correlation between the two.

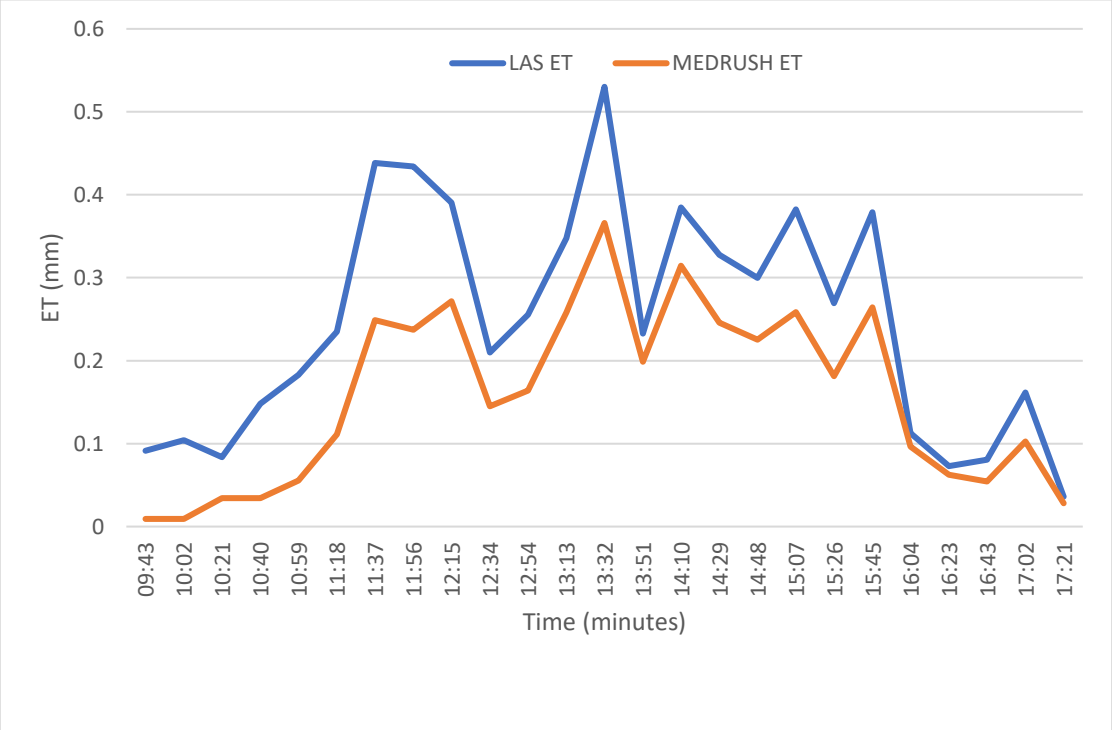

Figure 20: Daily evapotranspiration comparison between MEDRUSH and Large Aperture Scintillometer (LAS) for 23 December 2022

On the 23rd of December the correlation analysis revealed a strong positive relationship between the MEDRUSH model and observed evapotranspiration (LAS) with an R^2 value of 0.89. This indicates that there is a high degree of linear association between the MEDRUSH model's predictions and the actual observed evapotranspiration values. In other words, approximately 89% of the variability in observed

evapotranspiration can be explained by the variability in the MEDRUSH model's predictions (Figure 24).

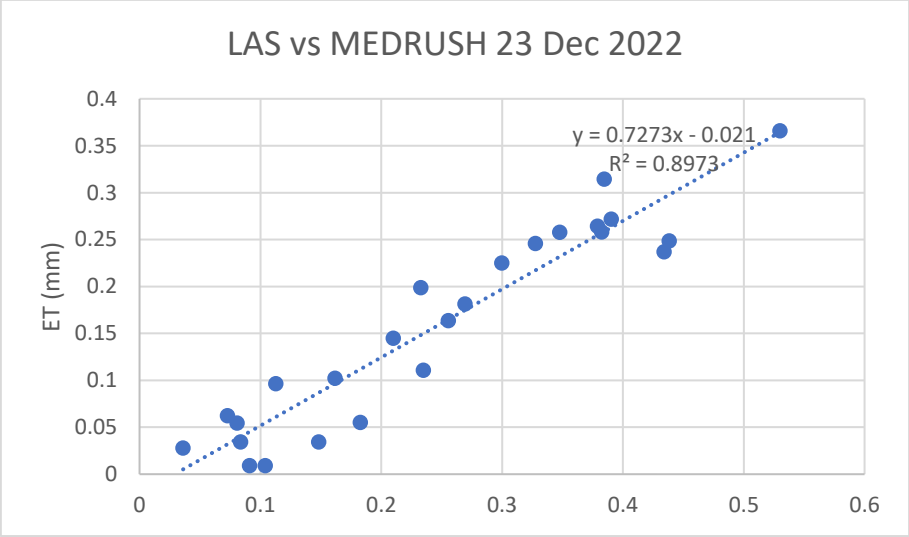

Figure 21: Correlation between MEDRUSH and Large Aperture Scintillometer (LAS) on the 23rd of December 2022.

On December 13, 2022, MEDRUSH and LAS initially exhibited a parallel trend from morning to afternoon. However, subsequently, there was a shift in the pattern, with LAS showing a decrease while MEDRUSH displayed an increase (Figure 25). On the 13th like the other days the model underestimated the daily LAS ET this can be seen during the morning when the two were following a similar trend. The 13th of December is an example when the model did not accurately predict the observed ET but nonetheless it was not the worst prediction because a trend between the two can be observed in the morning.

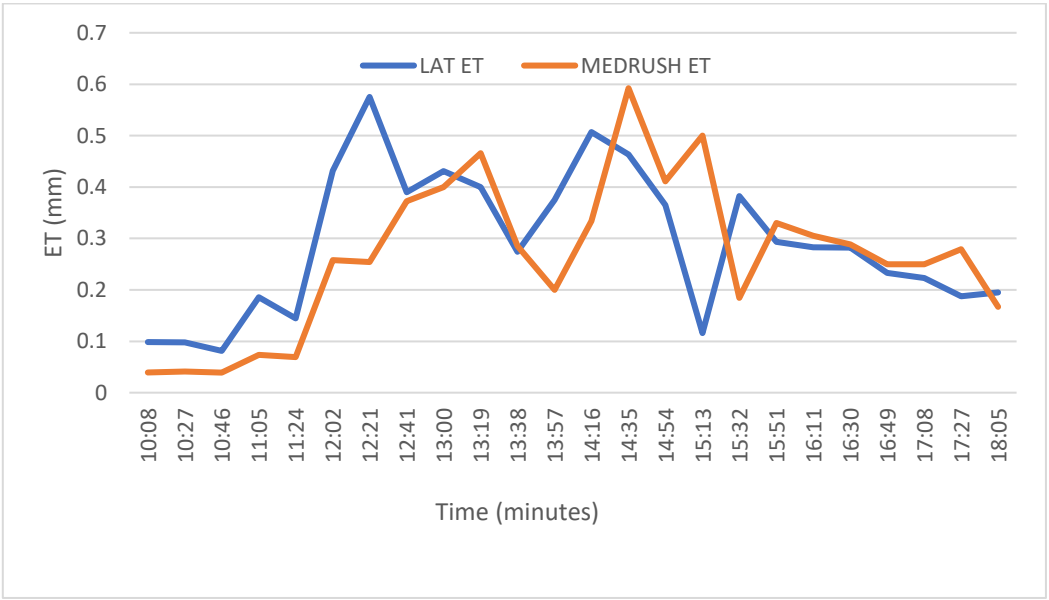

Figure 22: Daily ET comparison between MEDRUSH and Large Aperture Scintillometer (LAS) on the 13th of December 2022.

On the 13th of December 2022 the correlation analysis between LAS and MEDRUSH model revealed a moderate positive relationship between the MEDRUSH model and LAS with an R^2 value of 0.25. This indicates that there is a modest degree of linear association between the predictions generated by the MEDRUSH model and the actual observed evapotranspiration values. Approximately 25% of the variability in observed evapotranspiration can be explained by the variability in the MEDRUSH model's predictions (Figure 26).

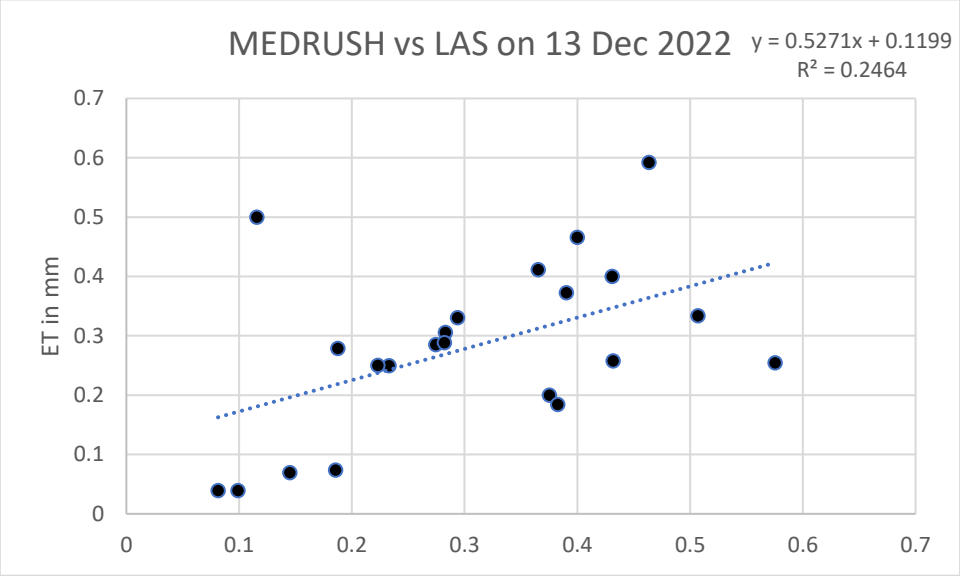

Figure 23: Correlation between LAS and MEDRUSH on the 13th of December 2022.

On December 17th, the performance of the MEDRUSH model was substandard. The model failed to accurately predict the evapotranspiration (ET) as measured by LAS. Notably, there was a lack of conformity in the trends between the model predictions and the actual ET. Consequently, this day marked the poorest estimation among all the measured days. (Figure 27).

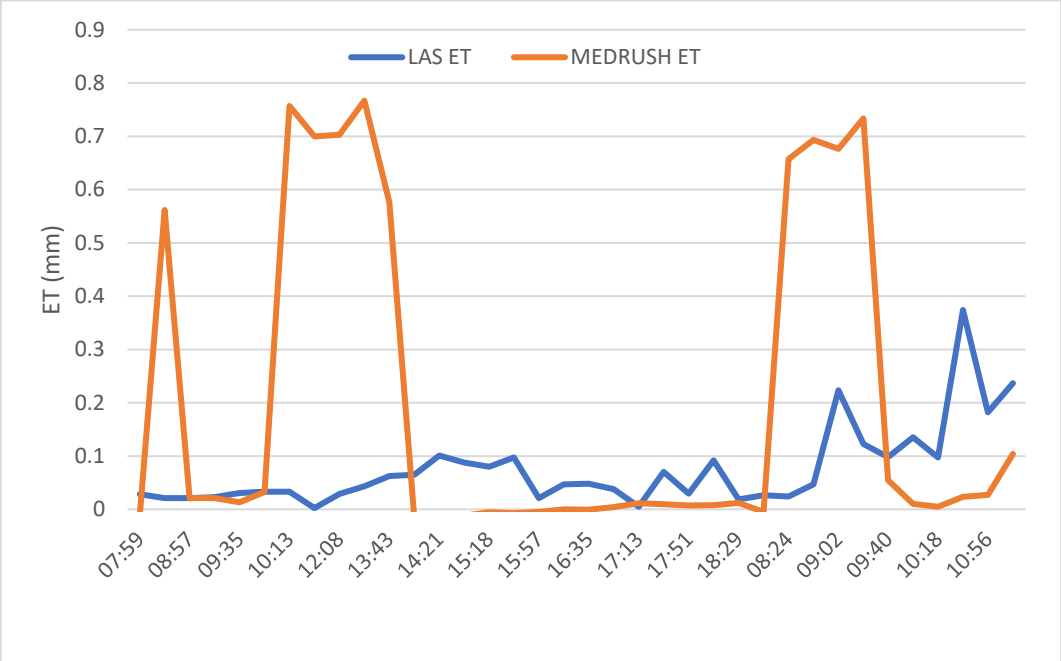

Figure 24: Daily ET comparison between MEDRUSH and LAS on the 17th of December 2022.

The correlation between LAS and MEDRUSH on the 17th of December shows R^2<0.01 which means less less than 1% of the variability in observed evapotranspiration can be explained by the variability in the MEDRUSH model's predictions. This means that there is no linear association between the predictions generated by the MEDRUSH model and the actual observed evapotranspiration values (Figure 28). The model was not able to adequately represent actual ET under very low radiation conditions.

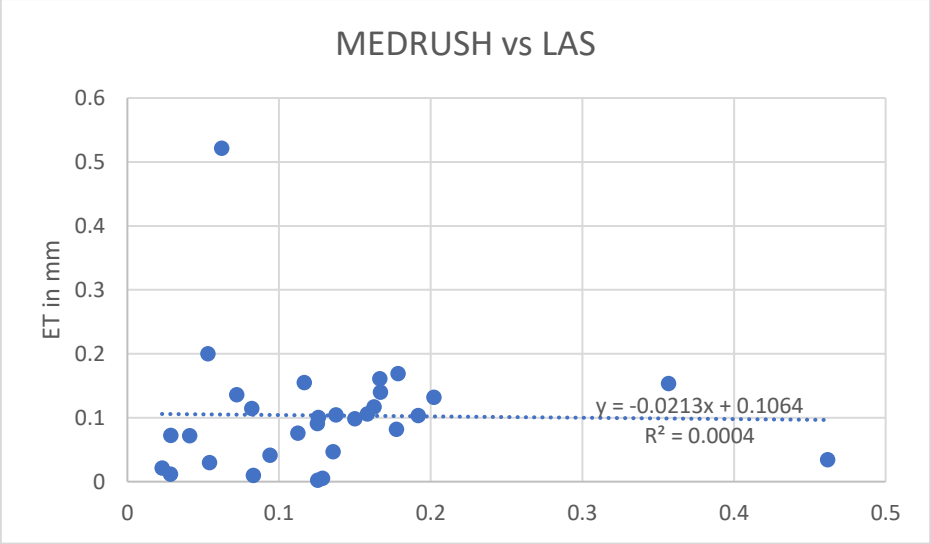

Figure 25: Correlation between LAS and MEDRUSH on the 17th of December 2022.

4.5 Measured physiological parameters at Firglen

Stomatal conductance

In December, *C. sativa* demonstrated the highest stomatal conductance (771.14 ± 156.44 mmol-m^{-2}-s^{-1}), whereas the lowest stomatal conductance was observed in January (604.45 ± 144.06 mmol m^{-2} s^{-1})). Despite these variations, stomatal conductance did not exhibit a discernible trend over the observed months (Figure 29). Statistical analysis results of the Kruskal-Wallis test revealed statistically significant differences between months ($p<0.05$). Pairwise Wilcoxon tests indicated that all months differed significantly from each other (all $p < 0.05$), except for December 2022 and February 2023, where the difference was not significant (Wilcoxon's test, $p > 0.05$).

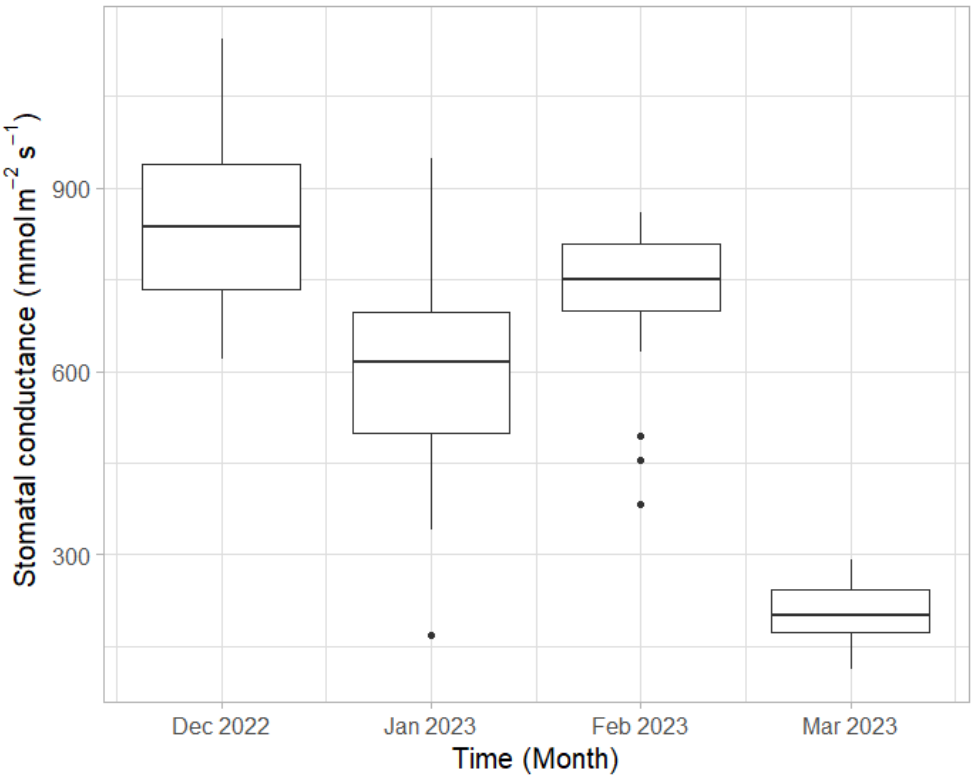

Figure 26: stomatal conductance of C. sativa measured during the growing cycle from Dec 2022 to March 2023.

Height

During the four-month growing cycle, plant height was systematically measured. A steady increase in height was noted from December to January, followed by a pronounced increase in growth between January and February. The tallest plants were recorded in March (1.24 ± 0.31), whereas the shortest plants were measured in December (0.61 ± 0.20), marking the initiation of measurements (Figure 30). There was a statistically significant difference in the plant height between months as assessed using the Kruskal-Wallis test ($p < 0.05$). Pairwise Wilcoxon tests between months showed that the difference between December and every other month was significant ($p < 0.05$).

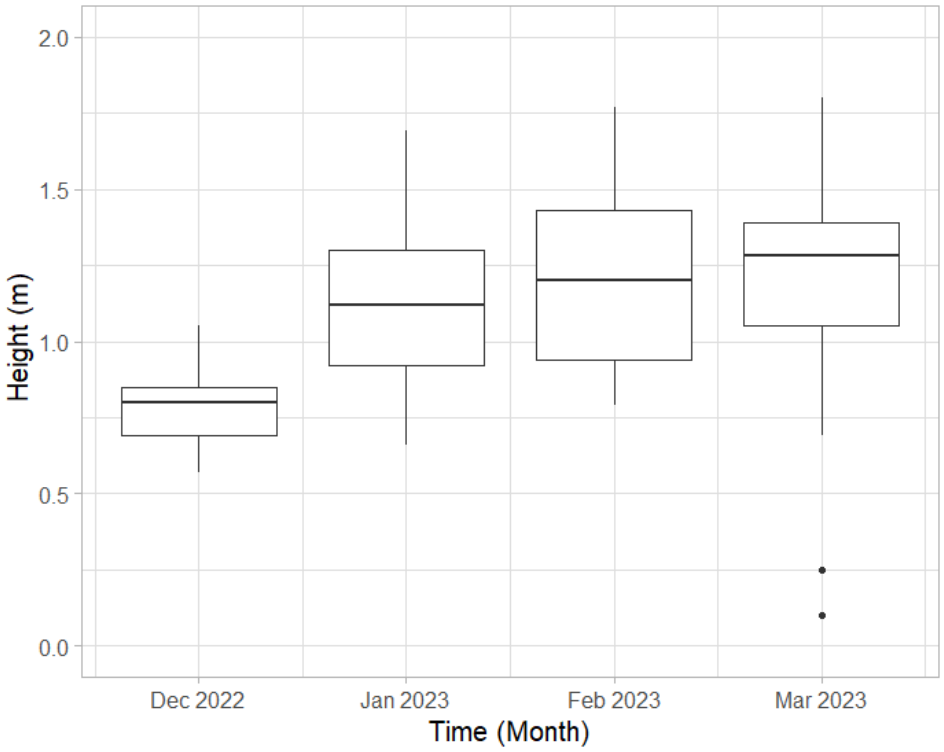

Figure 27: Height of C. sativa measured over a period of four months during the growing cycle

Canopy width

The canopy width of *C. sativa* was monitored over a four-month period. The findings indicate a progressive increase in plant width from December 2022 to March 2023. In December, the canopy exhibited the narrowest width (0.47 ± 0.24), while the widest canopy was observed in March (0.63 ± 0.31). The canopy width trend aligns with the height trend of progressive growth over the growing season (Figure 31). There was no significant difference in the plant canopy width between the months of the study (Kruskal-Wallis test, p >0.05.

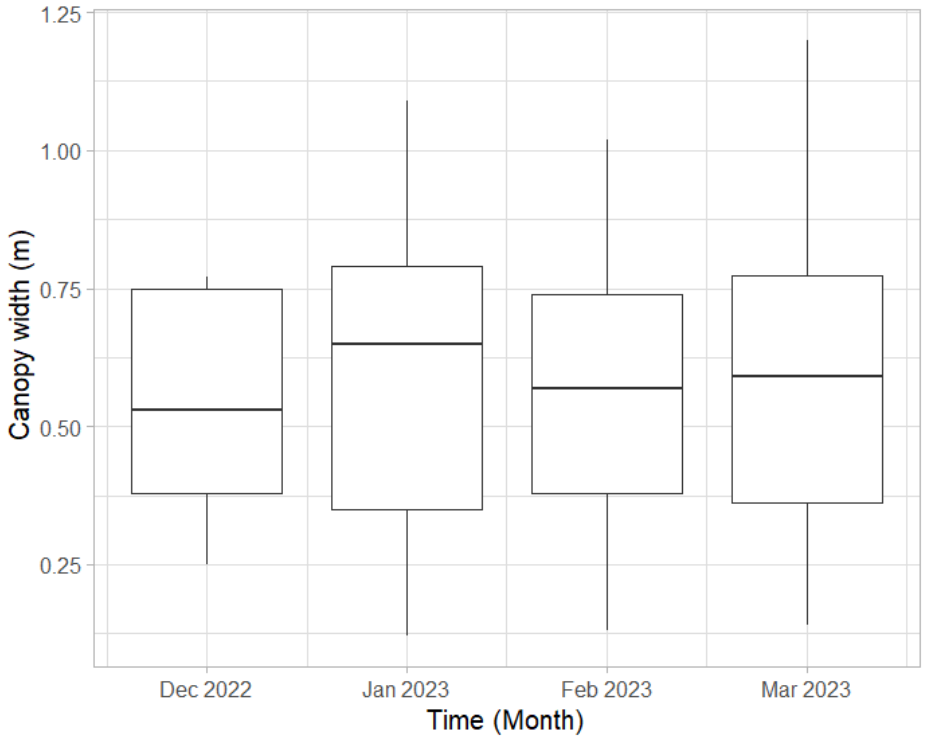

Figure 28: Canopy width of C. sativa measured over a period of four months during the growing cycle

Leaf Area Index

The Leaf Area Index (LAI) was assessed over a four-month duration spanning from December to March, coinciding with the growing cycle (Figure 32). A discernible trend in LAI was observed, indicating a gradual decrease from December to March 2023. In December, the highest average LAI was recorded at (2.52 ± 0.65), while March exhibited the lowest LAI at (0.08 ± 0.04). A Kruskal-Wallis test indicated there was a statistically significant difference in the mean *C. sativa* LAI between months ($p<0.05$). Each month in a pairwise comparison was significantly different (Wilcoxon tests $p<0.05$)

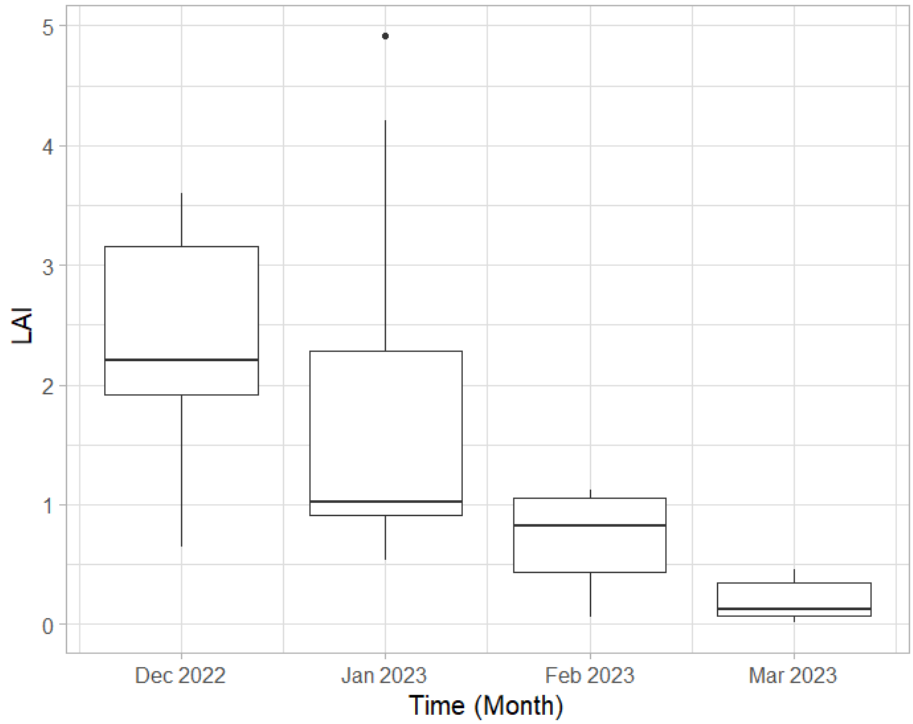

Figure 29: Leaf area index of C. sativa measured over a period of four months during the growing cycle

4.6 Harvest and yield

More than 90% of the cultivated *C. sativa* plants reached maturity within the five-month growing period. The harvested yield comprised 4202 g of good quality *C. sativa*, meeting expected standards for commercial-grade *C. sativa*. Additionally, 712 g of less than optimum quality *C. sativa* was obtained.

Chapter 5. Discussion

5.1 Introduction

In this chapter, we embark on a comprehensive discussion concerning the evapotranspiration (ET) dynamics of two distinct plant species, *C. sativa and E. plana*. The focal point of our analysis lies in explaining the differences and similarities between these species in terms of their ET, drawing from the results obtained through our outlined methodology. Central to our investigation is the utilization of the MEDRUSH model, a predictive tool for estimating ET, and an evaluation of its accuracy when juxtaposed with the LAS (Actual ET).

This study encompasses an exploration of the daily ET of *C. sativa*, providing insights into its water utilization patterns and comparing it with other plants. The MEDRUSH model, employed in this study, is instrumental in forecasting ET based on various environmental factors. We delve into the intricacies of this model and critically assess its predictive accuracy by comparing its estimates with the LAS-derived actual ET. This comparative analysis serves as a pivotal aspect of our investigation, offering insights into the reliability and applicability of the MEDRUSH model in the context of our specific plant species.

Furthermore, the discussion extends to the nexus between plant production and evapotranspiration, recognizing the intricate relationship that underscores the water use efficiency of these plants. The chapter explains how a plant's physiological health, particularly its ability to exercise stomatal control, plays a pivotal role in dictating its water consumption patterns. This consideration is vital, as it informs us about the water use of *C. sativa* in dryland cultivation and broader water resource management and agricultural practices

5.2 Comparative analysis of the Evapotranspiration of *Cannabis sativa* and *Eragrostis plana*

The daily mean evapotranspiration rate of *C. sativa* (1.76 ± 0.84 mm) exceeds that of *Eragrostis plana* (0.04 ± 0.068 mm). The difference in evapotranspiration (ET) between these two plant species can be ascribed to their contrasting sizes and leaf areas (Figure 33). *Cannabis sativa*, being a larger plant in comparison to *E. plana*, exhibits a greater leaf surface area and an overall larger transpiring surface, thereby contributing to elevated evapotranspiration rates (Jia and Wang 2021). Furthermore, the observed difference is influenced by the growth stages of the plants; *E. plana*, having been established in the field for a year, represents a mature plant, while *C. sativa*, grown for four months, is comparatively younger and in a more active growth stage, leading to increased water transpiration.

Previous research shows that other factors, such as genetics, environmental conditions, and physiological attributes, play pivotal roles in determining water use in plants (Denmead, 1984; Saugier and Katerji, 1991). Notably, plants cultivated in controlled environments, such as tunnels, exhibited higher daily evapotranspiration rates due to the greenhouse effect, especially in the absence of air conditioning. This underscores the significant influence of genetic, environmental, and physiological factors on a plant's evapotranspiration and overall water use (Denmead, 1984; Saugier and Katerji, 1991).

Despite the contrast in evapotranspiration rates between *E. plana* and *C. sativa*, certain similarities exist. For both species evapotranspiration is driven by high temperatures, elevated wind speeds, and radiation, characteristic of the summer months during which measurements were conducted. However, these shared environmental conditions do not negate the fundamental difference in water use between the two species. This insight into the water use of *C. sativa* compared to the local vegetation, represented by *E. plana*, underscores the higher water requirement of *C. sativa*. In addition to having a lower evapotranspiration rate, *E. plana* does not necessitate irrigation for growth, in stark contrast to *C. sativa*, which requires drip irrigation, particularly on extremely hot days. This contradicts the prevailing notion that *C. sativa* can thrive without agricultural inputs and functions as a “self-sustaining weed” (Højgaard, 2021).

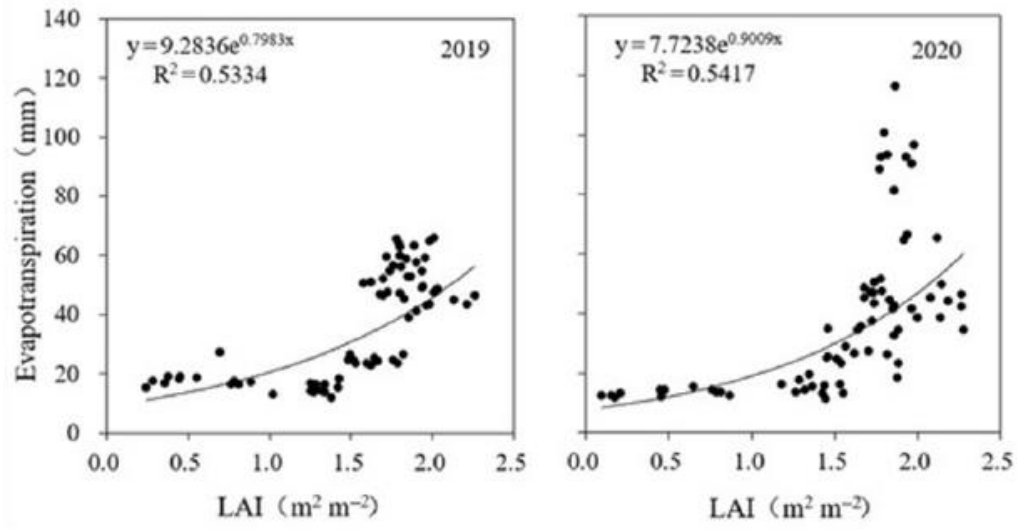

Figure 30: The relationship between evapotranspiration and leaf area index (taken from Jia and Wang, 2021).

The observed evapotranspiration (ET) dynamics of *C. sativa*, particularly in comparison to the local grass and other crops, reveal intriguing insights into its water utilization patterns. Despite *C. sativa* demonstrating a higher evapotranspiration rate than the local grass (*E. plana*), a comprehensive

examination of its average daily ET in relation to other crops, such as tomatoes and maize, illustrates noteworthy distinctions.

Drawing from Allen et al.'s work in 1998, it is evident that *Solanum lycopersicum* (tomato) exhibits a mean daily ET of 5 mm, a stark contrast to *C. sativa*'s measured daily average of 1.76 mm at Firglen study site. In the study by Allen et al 1998, the tomato crop was not subjected to the soil moisture stress that occurred under dryland conditions at Firglen. There was insufficient irrigation water to simulate these optimum growth conditions, as the study was designed to mimic the conditions that would be experienced by poorly-resourced legacy growers. Despite its higher evapotranspiration rate compared to local grass, *C. sativa* maintains a considerably lower daily water consumption than certain crops.

Further substantiating these findings, Gardiol et al. (2003) employed diverse evapotranspiration models, including the Penman–Monteith equation and the Shuttleworth and Wallace model. The crop was grown at two different plant densities (22,000 and 91,000 pl ha^{-1}), reaching maximum leaf area indexes of 1.5 and 5.5. Across all models, the ET for *Zea mays* (maize) consistently surpassed that of *C. sativa*, as illustrated in Table 4. This consistent pattern across various models reinforces the notion that under dryland conditions, *C. sativa*, while having a higher evapotranspiration rate than *E. plana*, consumes less water on a daily basis compared to crops such as maize.

The observed discrepancy in water consumption suggests that *C. sativa* exhibits a distinctive water-use efficiency strategy. This is further supported by the inference that *C. sativa* exercises a higher stomatal control, leading to reduced water loss through evapotranspiration when compared to crops like tomatoes and maize. This finding suggests that *C. sativa* may be employing an adaptive mechanism that helps it conserve and utilise water efficiently, making it a resource-efficient alternative in comparison to other crops.

Table 4: Daily mean Evapotranspiration of Zea mays measured using different ET models, P-M denotes Penman–Monteith and S-W denotes Shuttleworth–Wallace (taken from Gardiol et al., 2003).

Density (pl ha^{-1})	Model	Accumulated ET (mm)	Mean (MM/D)	Deviations (%)	*a* (mm)	*b*	R^2
22, 0000	Observed	386	3.9	-	-	-	-
	S-W	420	4.3	+15	5.60	0.83	0.79
	E+T	423	4.3	+15	4.31	0.89	0.81
91, 000	Observed	551	4.5	-	-	-	-
	P-M	539	4.4	-2	-2.55	-1.10	0.94
	S-W	650	5.2	+18	-1.30	-1.24	0.91
	E+T	556	4.5	+1	0.17	1.00	0.93

5.3 Measured physiological parameters at Firglen

Introduction

This sub-chapter aims to delve into the interplay of these physiological indicators, explaining their significance in gauging production during the cultivation process. These physiological indicators include stomatal conductance, leaf area index, heigh, canopy width and yield.

5.3.1 Stomatal conductance

Evapotranspiration is closely linked to stomatal conductance and both influenced by similar environmental factors such as temperature, radiation, wind speed, relative humidity and soil moisture (Allen et al, 1998). These factors affect the opening and closing of stomata which in turn affects the rate of evapotranspiration (Allen et al, 1998; Troung, 2012). Stomatal conductance (g_s) in plants is predominantly influenced by temperature, resulting in heightened g_s during warmer summer months (Saugier and Katerji, 1991).

The month of December, classified as a summer month, exhibited the highest stomatal conductance. Contrary to expectations, February, characterized by the highest average daily temperature, did not display the highest g_s. This discrepancy underscores that while temperature serves as a primary driver of g_s, it is not the exclusive determinant. Numerous factors, encompassing plant physiology and additional meteorological parameters, contribute to the observed variations (Saugier and Katerji, 1991). Among these factors, soil moisture emerges as an important determinant, as evidenced by its peak levels at Firglen during December, coinciding with the observed high stomatal conductance.

Following rainfall events and periods of abundant soil moisture, both stomatal conductance and evapotranspiration exhibit substantial increases thus explaining the high g_s in December (Miyashita et al., 2005; Leuning et al., 2008).

5.3.2 Leaf area index

Leaf Area Index, is a critical variable in botany and plant science, is used to describe the amount of leaf area within a specific landscape (Breda, 2003). Its significance lies in its utility for researchers in understanding a plant's photosynthetic capabilities and assisting in the determination of water and nutrient requirements (Breda, 2003). A high LAI is indicative of a healthy plant, as it signifies heightened photosynthetic activity, ultimately resulting in enhanced productivity and growth (Breda, 2003).

The measurement of LAI over the four-month period from December 2022 to March 2023 has provided valuable insights into the dynamics of plant canopy development throughout the growing cycle. The distinguishable trend in LAI showed a gradual decrease during this period, with noteworthy variations in monthly measurements. This observed decline in LAI carries significant implications for understanding the plant's physiological responses.

In December, the highest average LAI was recorded at (2.52 ± 0.65), indicating a healthy and extensive leaf canopy. This initial measurement served as a baseline, highlighting the robust foliage coverage at the beginning of the growing cycle. However, as the plants advanced through growth stages, a consistent decrease in LAI was observed, reaching its lowest in March 2023 at (0.08 ± 0.04). Several factors may contribute to this observed decrease, including environmental stress and limited resources. The nutrient deficiency in the Firglen soil emerged as a significant factor influencing the observed decline in LAI. This became evident when attempts to germinate seeds using local soil resulted in the failure of seed germination, suggesting a scarcity of nutrients. The gradual decrease in LAI over time can thus be attributed to plants extracting more nutrients from the soil, ultimately rendering it nutrient deficient. Additionally, leaf shedding played a role in the diminishing LAI, as observed instances indicated that certain plants experienced leaf loss over time. This phenomenon contributes to the reduction in overall leaf area, aligning with the observed trend in decreasing LAI.

The observed decrease in LAI over the four-month period can be attributed to a combination of environmental stress, limited resources, and nutrient deficiency in the soil. Future research needs to focus on addressing these limiting factors to optimize LAI for improved productivity.

5.3.3 Height and canopy width of *C. sativa*

The results of the four-month measurement of plant height and canopy width provided a valuable insight into the growth patterns of *C. sativa* during the observed growing cycle. This discussion aims to explain the observed trends, their temporal progression, and the correlation between plant height and canopy width.

The height measurements revealed a clear and steady increase from December to January, signifying early growth in the plants. Subsequently, a notable surge in growth occurred between January and February, culminating in the tallest recorded plants in March (1.24 ± 0.31). This surge in plant growth can be attributed to the increased availability of water during December and January, this further confirms that *C. sativa* thrives when ample supply of water is available. The initial measurements in December (0.61 ± 0.20) marked the baseline and indicated the onset of the growth cycle.

Simultaneously, the monitoring of canopy width presented a parallel narrative of progressive growth from December 2022 to March 2023. The canopy exhibited the narrowest width in December (0.47 ± 0.24), followed by a consistent increase, reaching its widest in March (0.63 ± 0.31). This aligns with the height trend, showing a synchronized growth pattern in both dimensions over the growing season.

The correlation between height and width trends implies a coordinated development of vertical and lateral dimensions, indicating a well-rounded and strong growth response in *C. sativa*. The synchronized growth patterns may be attributed to various factors, including genetics, environmental conditions, and resource availability such as water and nutrients (Denmead, 1984; Saugier and Katerji, 1991; Desanlis et al., 2013; Prato et al., 2022).

The correlation between height and width in *C. sativa*, will aid in the deeper understanding of the plant's development. This understanding in the intricacies of the plant's growth, sheds light on the duration required to attain specific heights and widths, indicative of maturity. Such insights, when utilised properly, empower legacy farmers, agricultural extension agents, and policymakers to make well-informed decisions regarding the cultivation of *C. sativa*. By understanding these developmental nuances, legacy farmers can optimize cultivation practices, contributing to more efficient and sustainable outcomes in *C. sativa* cultivation.

5.3.4 Yield

The high percentage of plants reaching maturity demonstrates the efficacy of the cultivation practices employed in this study. The harvested yield of good quality *C. sativa* ‘flos’ illustrates the potential for successful cultivation. The presence of less than optimum quality *C. sativa* suggests variability within the crop or potential areas for improvement in cultivation techniques. Further analysis of

environmental conditions, genetic factors, and cultivation methodologies may provide insights for optimizing yield and quality in future cultivation cycles.

5.4 Parametrisation

5.4.1 Comparing *C. sativa* and *E. plana* Models

This section will involve the discussion of how accurately the MEDRUSH model predicts the actual ET for *E. plana* and *C. sativa*.

The lower MAE, RMSE and RSR observed in *E. plana* indicate that the model was accurate at predicting the actual ET measured by the LAS. The model for *E. plana* was better at predicting daily ET when compared to MEDRUSH 10, which contained the parameters for *C. sativa*. Although *C. sativa* exhibits higher MAE, RMSE, and RSR values compared to *E. plana*, these metrics still indicate sufficient accuracy, implying that the model is relatively adept at forecasting the actual daily ET for both plant species**.** Thus indicating the accuracy and reliability of the model at predicting ET.

5.4.2 Model Evaluation

The model was able to accurately predict the actual LAS ET because it was observed that values for performance metrics such as MAE, RMSE and RSR which indicates that the model was accurate at predicting the actual ET were at their lowest. The PBIAS was negative on all these three days, which means the predicted values are lower than the observed values (LAS).

The coefficient of determination expressed as $R^2 = 0.63$ as illustrated in Figure 21 suggests a somewhat conservative estimation by the model. In summary, the model demonstrates a reasonable explanatory capacity with a notable R-squared value, and the derived regression equation shows the relationship between predicted and actual measured ET. The observed difference between the predicted (2.52 mm) and actual measured (1.76 mm) ET values implies an overestimation by the model in this particular dryland context. The observed overestimation by the model could not be attributed to the prevailing weather conditions, indicating that the model's overestimation occurs irrespective of elevated temperature days.

Despite this over-estimation the model is useful as it demonstrates a strong performance with a limited set of meteorological parameters. This adaptability makes it applicable to diverse landscapes and biomes worldwide. This adaptability was evident on numerous measuring days, particularly in on the 23rd of December, where a strong correlation between LAS and MEDRUSH was observed, with an R^2 value of 89.73. The high R^2 value suggests that the MEDRUSH model provides reliable estimations of evapotranspiration, demonstrating its utility in hydrological modelling and prediction.

This model proves well-suited for regions in the global South, where challenges such as data scarcity and financial constraints are common. The cost-effective nature of this model becomes particularly advantageous in such areas, where acquiring and maintaining expensive equipment like eddy covariance and scintillometers may be impractical.

5.5 Meteorological Characteristics of the Firglen study site

The Firglen study site exhibits meteorological patterns found in the wider Eastern Cape, characterized by hot and wet summers, coupled with cold and dry winters (Mahlalela et al., 2020). This climatic profile is evident in the precipitation levels during December, the elevated temperatures from November to February, and the lower temperatures observed between May and August. In addition to these weather conditions, the region is susceptible to Bergwinds, which pose a threat to *Cannabis* crops due to excessively high air temperatures, elevated wind speeds, and reduced soil moisture. Bergwind events are prevalent in the Eastern Cape Province (Prof A.R. Palmer, personal communication, 2022), particularly during the growing season when crop failure can occur.

The success of this crop can be primarily ascribed to the consistent availability of water, predominantly facilitated by natural rainfall patterns and drip irrigation on extremely hot days. Throughout the crop cycle, the cultivated plants benefitted from a total precipitation of 154 mm, averaging approximately 2 mm per day. This observation underscores the critical role of water as a limiting factor in the cultivation of *C. sativa*, emphasizing the necessity for proactive measures to ensure its adequate provision and management within cultivation practices.

5.5.1 Wind speed

Wind speed is one of the parameters or factors that play a significant role in the rate of evapotranspiration. This is due to the fact that higher wind speeds lead to higher evapotranspiration rates (Tolk et al., 2006). The average wind speed that could lead to an excessive evapotranspiration rate is between 2 to 4.4 m sec^{-1} (Tolk et al., 2006). The plants at Firglen were regularly exposed to wind speeds of more than 2 m sec^{-1}, and on some days, the wind speed went up as high as 12 m sec^{-1}. These high wind speeds have led to some physical damage to plants, thus reducing the plant's ability to exercise optimal stomatal control due to their compromised physiological state. It is therefore, imperative that growers consider the wind speed of the area they want to cultivate, especially in semi-arid environments, because high wind speed coupled with high temperatures could lead to crop failure. Growers are strongly encouraged to plant windbreaks of Napier fodder (*Pennisetum purpureum*) or some other appropriate, non-invasive species (Brandle et al., 2004).

5.5.2 Soil moisture

The findings of this study shed light on the relationship between soil moisture content and the growth of *C. sativa* at Firglen, a region characterized by its reliance on summer rainfall. The highest average soil moisture content, observed in December, correlates with the substantial rainfall experienced during this period. This aligns with the well-known climatic pattern of the Eastern Cape, which typically receives summer rainfall. Conversely, April exhibited the lowest soil moisture content, further affirming the seasonal nature of rainfall in the region. Given *C. sativa's* dependence on moisture for optimal growth, these results underscore the importance of planting this crop during periods of ample rainfall to minimize reliance on irrigation, particularly in water-scarce regions like South Africa.

This research indicates that *C. sativa* thrives when soil moisture levels are maintained at approximately 23%. However, the average soil moisture content at the study site was recorded at around 17% in 2021 to early 2022, falling short of the ideal conditions for optimal growth, but in late 2022 during the experimental growing cycle the average soil moisture had risen to 22.15% which is much higher than the previous soil moisture content. To address this, it is crucial to implement strategies to manage soil moisture effectively. Cost-effective and sustainable irrigation methods, such as drip irrigation, which was employed in this study, can play a vital role in maintaining adequate moisture levels for *C. sativa* cultivation. Additionally, exploring alternative techniques like fog harvesting offers promising solutions with minimal environmental impact, particularly for small-scale rural growers in water-scarce regions (Olivier, 2004). By implementing these practices, growers can enhance the success and sustainability of *C. sativa* cultivation while minimizing water usage and promoting environmental conservation in alleviating the stress exerted on the water supply of the Eastern Cape and South Africa as a whole.

5.5.3 Temperature

Temperature emerged as an important meteorological parameter at the Firglen site. Understanding temperature variations is important for assessing the climatic conditions of an area and determining its suitability for cultivating *C. sativa*. The dataset revealed significant insights into the thermal environment of Firglen, particularly during the summer months, where temperatures reached 40 ˚C. The observed difference between temperatures recorded by the lower and upper thermocouples is an important finding. The higher temperatures measured by the lower thermocouple, closer to the surface, compared to the upper thermocouple, can be attributed to the Earth's surface's absorption of solar radiation (Allen, 1997). This absorption results in the conversion of solar energy into heat, leading to elevated surface temperatures (Allen, 1997). This phenomenon emphasizes the influence of solar radiation on surface heating dynamics, *C. sativa* cultivation practices.

The implications of these high surface temperatures are significant, particularly concerning plant physiology. High temperatures pose a risk to plants, potentially leading to wilting and, ultimately, plant mortality. The observed thermal conditions highlight the importance of understanding and mitigating the adverse effects of heat stress on crop cultivation, especially in regions prone to high temperatures.

Additionally, the findings underscore the importance of incorporating climatological parameters, such as temperature, into agricultural decision-making processes. By gaining insights into the thermal conditions of an area, researchers and growers can anticipate and prepare for potential challenges associated with temperature extremes. In the case of Firglen, the knowledge of high summer temperatures informed the decisions regarding irrigation strategies in order to mitigate the adverse effects of heat stress on crop productivity.

Chapter 6. Conclusion

In conclusion, the two-year research journey aimed to understand the water utilization patterns of *Cannabis sativa*, employing a combination of direct measurements using Large Aperture Scintillometer (LAS) and modelling with the MEDRUSH model. Through rigorous experimentation and methodological innovation, the reasearch successfully addressed various challenges encountered along the way. This study demonstrates that the MEDRUSH model effectively predicts the water use of *C. sativa* when compared to actual evapotranspiration (ET) values obtained from LAS measurements. Importantly, the model's ability to adapt to diverse meteorological parameters suggests its potential for broader application across different landscapes and ecosystems, particularly in regions with limited data availability and financial resources like the global south.

This study reveals that *C. sativa* exhibits a reduced daily mean ET when compared to other crops like maize (*Zea mays*) and tomatoes (*Solanum lycopersicum)*, suggesting its potential suitability for cultivation in water-sensitive regions such as the Eastern Cape. This finding has significant implications for agricultural practices, informing stakeholders such as government officials and legacy farmers about the most appropriate crop varieties for water conservation efforts. Moreover, our research delved into the intricate relationship between stomatal conductance, soil moisture, and environmental factors, shedding light on the mechanisms governing *C. sativa's* response to its surroundings. Notably, this study indicates that optimal cultivation of *C. sativa* occurs during the early summer months of October and November to capitalize on subsequent summer rains in December. Strong winds and high temperatures had a detrimental effect on plant growth and overall crop success. These findings offer valuable guidance for legacy farmers seeking to adapt their cultivation practices for successful crop outcomes.

Through the examination of growth activity, stomatal conductance, and leaf area index (LAI), valuable insights into the physiological dynamics of plant development have been gained. Stomatal conductance, influenced by environmental factors like temperature and soil moisture, revealed fluctuations throughout the observed period, highlighting the intricate relationship between plant physiology and environmental conditions. Height and canopy width measurements demonstrated synchronized growth patterns in *C. sativa*, reflecting the plant's response to varying resource availability. The decline in LAI over time, attributed to environmental stress and nutrient deficiency, underline the importance of addressing limiting factors to optimize plant productivity.

Furthermore, this study validated findings from cultivation in other regions, such as the plant's requirement for a constant water supply for growth and vitality (Lisson, 1998)

New measurements for semi-arid dryland systems have been made to contribute to the growing ecophysiological research into *C. sativa*. *C. sativa's* daily mean evapotranspiration which was measured at 1.76 mm. This provides guidance for improving cultivation practices and buffering farmers from environmental shocks, particularly in regions prone to water scarcity and climatic variability.

Additionally, this study highlights the susceptibility of *C. sativa* to adverse weather conditions such as strong winds, high temperatures, and water scarcity, underscoring the importance of strategic planting decisions and protective measures like windbreaks. It is recommended that planting be done at the beginning of summer to coincide with the rainy season, thereby reducing reliance on irrigation and mitigating the risk of crop failure associated with severe weather events such as very high temperatures

In conclusion, the project contributes valuable insights into the water use dynamics of *C. sativa*, offering practical recommendations for sustainable cultivation practices in water-scarce regions like the Eastern Cape. Moving forward, continued efforts in improving the efficacy of the MEDRUSH model and employing other ET models is essential to refine our understanding of crop-water interactions and promote resilient agricultural systems in the face of climate change.

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