Measurement and modelling of *Cannabis sativa* L. evapotranspiration, KwaZulu-Natal Midlands, South Africa.

by

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Agrometeorology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa. The research was financially supported by the Water Research Commission (WRC), project number C2021/2022-00442 (Determine water-use of cannabis tree in Eastern Cape and KwaZulu-Natal Provinces).

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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Supervisor: Alistair Clulow

Date: 29 November 2024

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Co-supervisor: Trevor Hill

Date: 29 November 2024

DECLARATION ONE: PLAGIARISM

I, Gary Mark Denton, declare that:

(i) the research reported in this thesis, except where otherwise indicated or acknowledged, is my original work;

(ii) this thesis has not been submitted in full or in part for any degree or examination to any other university;

(iii) this thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this thesis is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

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Signed: Gary Mark Denton

Date: November 2024

DECLARATION TWO: PUBLICATIONS

This dissertation is written in manuscript format. Details of my contribution to each manuscript, as well as contributions by others, that form this dissertation, are indicated.

Chapter Two

The data reported were obtained by G. M. Denton over the monitoring period. The equipment setup, system maintenance and data collection, was conducted by G. M. Denton, and data were processed, analysed and interpreted by such, with the assistance of A. D. Clulow, V. Naiken and T. Hill. The data reported will be submitted to the journal, *Plant and Soil*, for publication.

Chapter Three

The research reported were based on the information collected by G. M. Denton that took place in the same location during the same period as that reported in Chapter Two, hence there may be an overlap of information. All data were obtained, analysed, and interpreted by G. M. Denton, with assistance provided by A. D. Clulow, T. Hill and S. Gokool. The data reported will be submitted to the journal, *Agriculture,* for publication.

[redacted]

Signed: Gary Mark Denton

Date: November 2024

ABSTRACT

The South African National Water Act (No. 36 of 1998) mandates the regulation of land-based activities that reduce streamflow by declaring them streamflow reduction activities (SFRAs). Hemp (*Cannabis sativa* L.) is commonly known as a water-intensive crop, yet no measurements of its evapotranspiration (ET) exist in South Africa. Therefore, its impact on streamflow reduction cannot be assessed. This study provides ET data to determine if irrigated hemp should be investigated further as a potential SFRA by determining its ET and water productivity. An eddy covariance (EC) system was utilised in a hemp field trial at a commercial farm in KwaZulu-Natal (29º31'37.0" S, 30º28'03.2" E). Approximately 7 ha of hemp was planted on 21 November 2022 and harvested on 15 April 2023. Standard microclimatic variables and the volumetric soil water content, plant height and Leaf Area Index (LAI) were measured. To extrapolate the field measurement results beyond a point measurement to assess spatial difference in water use, a remote sensing modelling approach was applied to derive ET using multispectral drone imagery. It was found that although there is still a deficit in the modelling applications involving hemp, the QWaterModel was potentially a suitable modelling platform, chosen due to its operational simplicity. The EC measurements indicate that the total ET from the hemp crop over the growing period was 377 mm. The average daily volume of ET was 28.4 L tree^{-1}, or 2.94 mm plant^{-1} as a depth. The crop coefficient varied between 0.63 and 0.76 throughout the season and the water productivity of hemp (kg of fresh bud per m^{-3} of water) was 0.96 kg m^{-3}. Hemp had a high water use and low water productivity compared to other international hemp studies. This may be partly due to the higher planting density reported in other international studies (2 000 plants ha^{-1} vs. 300 000 – 2 400 000 plants ha^{-1}), and partly due to factors such as light or soil nutrients. The QWaterModel was found to overestimate ET over the season, with an accumulated ET_{QW} of 24.2 mm being modelled over five flights (five days) throughout the season, while the EC system measured approximately 16.9 mm ET_{EC} over the same period. However, a good correlation was observed between QWaterModel and ground-based EC measurements. The lack of canopy closure affected the estimation of ET, as the single-source QWaterModel is unable to differentiate heterogeneous canopies. The remote sensing approach depicted the variability of ET across the field, with higher ET taking place due to differences in topographical elevation, and therefore the soil depths of the field. These results provide the first water use and crop coefficient estimates of hemp in South Africa and provide data required to assess the streamflow reduction activity of hemp.

ACKNOWLEDGEMENTS

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Thank you to Vivek Naiken, my support technician, for all his help in the field and the contributions he made to this project. He played a pivotal role in the practical preparation and running of the fieldwork.

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A very special thanks goes out to Trevor Hill for his contribution to my writing skills and for the escapades to the Western Cape that made many memories during the period of this research.

Thank you to my peers and colleagues: Ameera Yacoob, Knowledge Muchaonyerwa and Evania Chetty, who played an important part in my daily activities and kept me motivated.

A very special thank you goes to the farming business for their collaboration and allowing us unlimited access to their crop for data collection.

Thank you to the WRC, project number C2021/2022-00442 (Determine water-use of cannabis tree in Eastern Cape and KwaZulu-Natal Provinces) for their funding and to the reference group for all their guidance and input into the project. Thank you to Sukh Mantel, Trevor Palmer and the rest of the project team for their support and guidance.

And finally, to my family and my friends, who were always there for me and who were my biggest support group– their presence was unparalleled in getting me through.

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LIST OF ABBREVIATIONS

ET	Evapotranspiration
EC	Eddy covariance
THC	Tetrahydrocannabinol
DAFF	Department of Agriculture, Forestry and Fisheries
DWS	Department of Water and Sanitation
SFRA	Streamflow Reduction Activity
LAI	Leaf Area Index
UAV	Unmanned Aerial Vehicle
WRC	Water Research Commission
FW	Fine Wire
LE	Latent Energy
VWC	Volumetric Water Content
ETo	Reference evapotranspiration
Kc	Crop coefficient
WP	Water Productivity
WUE	Water Use Efficiency
EF	Evaporative Fraction
LST	Land Surface Temperature
ET_{QW}	QWaterModel ET
ET_{EC}	Eddy covariance ET

CHAPTER ONE
INTRODUCTION

1.1 Introduction

There is an increasing interest in *Cannabis sativa* L. due to its array of applications as a multipurpose crop within South Africa, as it can be cultivated for fibre, seed, oil, and medicinal purposes (Amaducci *et al*. 2015). While both hemp and marijuana are derived from the same *C. sativa* L. family, the former has less than 0.3% tetrahydrocannabinol (THC) and is primarily grown for its fibre or seed production. In South Africa, a license from the South African Health Products Regulatory Authority and a permit from the Director General of the National Department of Health are required to commercially cultivate *C. sativa* L., regardless of its THC content. However, cultivation of *C. sativa* L. for personal consumption, by an adult in a private setting, is exempt from this regulation (Institute for Economic Justice, 2023).

South Africa is facing a critical shortage of water, with increasing demands for the limited water resources available (DWS, 2021). Agriculture currently accounts for 66% of South Africa's water usage. Therefore, any plans to cultivate a potentially high water-consuming crop requires a detailed study of the crop's water use, potential impacts on water resources, and downstream water availability. Failure to conduct such investigations may compromise the necessary knowledge to ensure adequate water provision for citizens and sustainable development (DWS, 2021).

Hemp, which has been cultivated for thousands of years (Sawler *et al*. 2015), is a crucial fibre crop that serves a wide range of purposes (Visser, 2013). Its versatility allows it to be used in an array of industries from clothing, textiles, paper, compressed wood products, cosmetics, to energy production, particularly in biomass and bioenergy. Furthermore, hemp has environmental benefits, including phytoremediation and carbon sequestration (Adesina *et al*. 2020). However, the stigma surrounding hemp, due to its association with marijuana, and legal restrictions has hindered its widespread cultivation in South Africa, resulting in the country being a net importer of hemp fibre and seeds (DAFF, 2012).

Cannabis sativa L. is globally the most sought-after illicit drug (United Nations Office on Drugs and Crime, 2011; Houmi, Mohamadi and Balz, 2018) and therefore limitations on its cultivation exist. However, several countries, including Uruguay, Canada, and Colorado State in the USA, have legalized cannabis, citing potential tax revenue benefits, economic spinoffs, investment, and employment opportunities, as drivers for this legalisation (Baldavoo & Hassen, 2024).

Despite the anecdotal evidence that small-scale farmers are widely cultivating hemp within the province of KwaZulu-Natal, successful cultivation practices are not well documented. However, it is believed that hemp could be a feasible, high-value crop for emerging small-scale farmers (Nath, 2022). Critically in the South African context, the water use of hemp remains largely unknown, though it has been referred to as a water-thirsty plant (Ashworth & Vizuete, 2017). There are only a few estimates available in the international literature. Bauer *et al*. (2015) stated that hemp used 22.7 L plant^{-1} day^{-1} over the three-month growing season in California, USA (Humboldt County Outdoor Medical Cannabis Ordinance Draft, 2010, in Bauer (2015)), and this is cited in later studies by Butsic and Brenner (2017) and Butsic *et al*. (2017) for the same area. By way of comparison, the measured mean daily evapotranspiration of a five-year-old *Eucalyptus grandis* tree, which has been proclaimed a SFRA, planted in a high rainfall area of South Africa, was 5 and 50 L tree^{-1} day^{-1} for winter and summer season, respectively (Gush *et al*. 2015).

Due to a growing interest in promoting the cultivation of hemp in South Africa, it is essential to determine its evapotranspiration and the associated impacts on the hydrological response. The understanding of ET variability across the field will inform growers in the management of groundwater and potentially make significant water savings. Furthermore, it will help make informed decisions regarding hemp cultivation, preventing adverse impacts in an already stressed water catchment.

1.2 Research Aim and Objectives

The knowledge and recognition of hemp as a high-value crop, combined with anecdotal evidence of its successful cultivation, have led to suggestions of its significant potential for small-scale emerging farmers in rural areas of KwaZulu-Natal. However, to ensure the feasibility and sustainability of this activity, it is necessary to investigate its production potential and potential impact on water resources, in areas that are already water scarce. Furthermore, the South African National Water Act (No. 36 of 1998) mandates the regulation of land-based activities that reduce streamflow by declaring them a SFRA. While it is widely known that hemp is a water-intensive crop (Zheng *et al*. 2021), no field-based measurements of its ET exist in South Africa.

The aim of this study was to calculate the evapotranspiration and water productivity of hemp over a season of growth in the KwaZulu-Natal Midlands, South Africa. This research provides water use and crop modelling data to support the evaluation of dryland hemp as a potential SFRA.

The objectives of the research are to:

- quantify the ET losses and crop coefficient for a hemp crop over a growing season;
- determine the water productivity of hemp; and
- assess a remote sensing technique to understand ET variability across a cultivated field.

1.3 Thesis structure

Following the ‘acceptable formats for a dissertation’ as outlined by the University of KwaZulu-Natal (UKZN), this dissertation is structured ‘as a set of papers which are published, in press, submitted, or intended for submission’. Chapters two and three are written for publication, including relevant literature, materials and methods, results, discussion, and conclusions as outlined below.

The dissertation structure ‘as a set of papers’ inevitably includes some overlap between chapters, primarily in the description of the study area, which they have in common, and the description of the meteorological models used to estimate ET. The focus of each paper, however, differs in measurement strategy employed, aim and outcome, contributing together towards an improved understanding of the water-use of hemp within the KwaZulu-Natal area. As recommended by the UKZN in the ‘acceptable format for a dissertation’, the references have been included at the end of each chapter in a style that conforms to the relevant journal in which that paper will be submitted.

Chapter two focuses on the measurement of hemp ET over a single growing season, using the eddy covariance technique. It provides an understanding of the evaporation dynamics of the crop. Chapter three focuses on the ET demand of hemp by using a UAV to obtain thermal images of the crop, which were used to model the spatial variation in ET using QWaterModel.

Results were compared to that from the eddy covariance system. This research work occurred over the same location and period as that in chapter two.

Chapter four is a synthesis chapter and integrates research, discusses the implication of results obtained and identifies future research possibilities.

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CHAPTER TWO
WATER USE AND PRODUCTIVITY OF CANNABIS IN THE KWAZULU-NATAL MIDLANDS, SOUTH AFRICA

2.1 Abstract

Accurate hydrological data are imperative in improving water management in water-scarce areas. This research provides measurements of the evapotranspiration of hemp over a growing season, providing a crop coefficient and water productivity, for the planning and implementation of the expanding hemp industry in South Africa. The study utilised an eddy covariance system in a hemp field trial at a commercial farm, KwaZulu-Natal, South Africa. Approximately 7 ha of hemp was planted on 21 November 2022 and harvested on 15 April 2023. Standard meteorological variables were measured, along with the surface energy and radiation balances, volumetric soil water content, plant dimensions and Leaf Area Index. The total ET over the growing period was 377 mm, with the average daily ET being 2.94 mm day^{-1} or 28.4 L $tree^{-1}$. The monthly crop coefficient varied between 0.63 and 0.76 throughout the season and the water productivity of hemp (kg of fresh bud per m^{-3} of water) was 0.96 kg m^{-3}. It was concluded that the hemp trial had a high water use and low water productivity compared with other international studies.

2.2 Introduction

Cannabis sativa L. is grown under diverse conditions in both temperate and tropical environments (Cosentino *et al*. 2012; Clarke and Merlin, 2016). It was declared illegal in South Africa in 1928 (Perkel, 2005), however since 2018, legislation allows for the private cultivation and consumption of small amounts of cannabis (Institute for Economic Justice, 2023). Prade *et al*. (2011) summarised that *Cannabis sativa* L. is grown in the USA, Ireland, Spain, Germany, and Poland for biofuel purposes. Its history within South African legislation is summarised in a report by the United Nations Office on Drugs and Crime (2002), which states that cannabis cultivation in South Africa has been identified to be most prevalent in the provinces of the Eastern Cape and KwaZulu-Natal.

Cannabis sativa L. is divided into two subspecies depending on their chemical composition and hence their usage. *C. sativa* L. is classified as hemp if the delta-nine-tetrahydrocannabinol

(THC) content is less than 0.3%, whilst a THC percentage higher than 0.3% classifies the plant as marijuana (Wimalasiri *et al*. 2021). While hemp is grown for agricultural purposes (fibre and seed) and medicinal applications (cannabidiol and oil), marijuana is typically grown for personal consumption. Hemp is reported as being a high yielding multi-purpose crop with low inputs (Struik *et al*. 2000). However, water and nitrogen deficiencies are two major constraints facing the hemp cultivation industry (Cosentino *et al*. 2013; Tang *et al*. 2017). Nitrogen deficiency is typically addressed through application of appropriate fertilizers for optimum growth (Cosentino *et al*. 2007; Campiglia, Radicetti and Mancinelli, 2017; Tang *et al*. 2017), whereas water deficiency is addressed through irrigation. The implementation of irrigation schedules accompanying precision agriculture, requires knowledge regarding the crop water use, however, literature recommendations for the water requirements (henceforth known as evapotranspiration) of hemp are ambiguous: in a global summary provided by Pejic *et al*. (2018), hemp requires 250 – 280 mm in Ukraine, citing Kisgeci (1994); in the Netherlands hemp is claimed to require at least 650 mm rainfall, citing Van Dam (1995); in Tasmania, Australia, hemp requires 535 mm over a growing cycle, citing Lisson and Mendham (1998); and Bocsa and Karus (1998) reported ET of up to 700 mm in eastern Europe over the growing season. Unfortunately, all these studies cited by Pejic *et al*. (2018) were either not peer-reviewed or were inaccessible and could therefore not be verified.

A study by Cosentino *et al*. (2013), noted an ET of 320 mm over a full growing season of hemp in a semi-arid Mediterranean climate, while Bajić *et al*. (2022) observed that hemp's ET ranged from 450 to 520 mm over a two-year period, across three hemp variants in Serbia. Both these studies applied the Class-A pan reference evaporation method by estimating a crop coefficient (Kc) to estimate ET. However, Bajić *et al*. (2022) obtained Kc from Cosentino *et al*. (2013) who did not specify how Kc was estimated. This means that Kc cannot be validated, potentially leading to discrepancies in ET calculations for both studies. Thevs and Aliev (2022) used sap flow measurements and found that hemp's ET was 353 mm in northern Kazakhstan over the growing season; since sapflow measurements were spatially and temporally limited, measurement data were extrapolated to fill in data gaps. Thevs and Nowotny (2023) found that ET averaged 343 mm over a four-year trial in northern Germany using the S-SEBI remote sensing model but lacked *in-situ* data and validation. However, the ET of hemp has not been measured using the eddy covariance technique, which remains one of the most steadfast methods of ET measurement, offering non-intrusive, direct measurement at a high temporal resolution (Burba, 2021).

The lack of sufficient scientifically sound information on hemp ET is particularly problematic in water scarce countries such as South Africa (Otieno & Ochieng, 2004) where there is the potential for significant expansion of the hemp industry. This study determined the ET of hemp using *in-situ,* field-based measurements and provides estimates of Kc that would need to be adjusted depending on local climatic conditions and crop management practices. These adjustments ensure that the ET of hemp can be estimated across different climates in different parts of the world using the internationally accepted FAO-56 Penman-Monteith method (Allen *et al*. 2006). As ET estimation incorporates the conjunctive use of a crop coefficient and reference evaporation, the influence of the local climate, specific to the study's area, is included, allowing for the calculation of ET specific to that region.

2.3 Methods

2.3.1 Study Site

The study site (29°31'37.0" S, 30°28'03.2" E) was located on a commercial farm near Pietermaritzburg in the province of KwaZulu-Natal, South Africa (Figure 2.1). A seven-ha area of *Cannabis sativa* L. was planted in late November 2022 and was managed, weeded and irrigated by the local farming business. An electrified fence surrounded the site for security purposes.

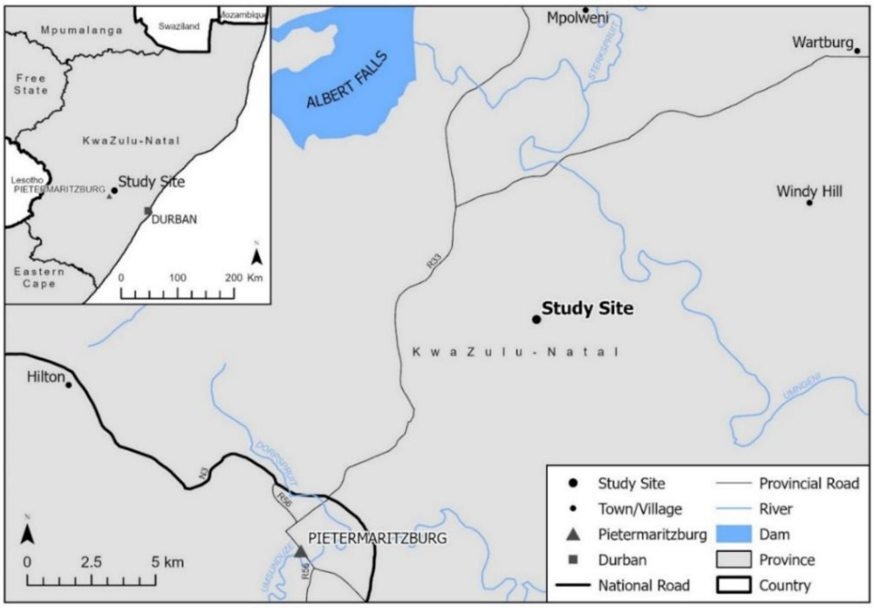

Figure 2.1: Trial site situated within KwaZulu-Natal, South Africa

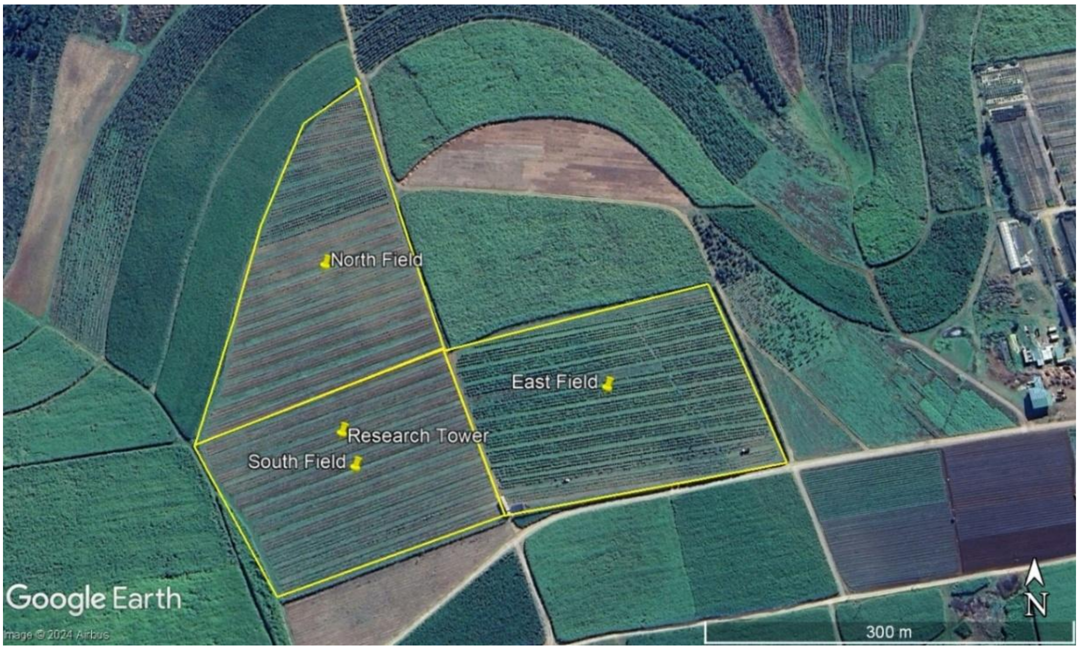

Plate 2.1: The three hemp fields and position of the measurement tower (Google Earth image, accessed 05/08/2024).

The crop was partitioned into three fields, to the North, East, and South sides. The South field contained feminized *C. sativa* L. seedlings (landrace: Charlotte's Angel), while the other two plots (North, East) contained *C. sativa* L. clones (landrace: Cherry Blossom; Plate 2.1).

Seeds and clones were germinated in a greenhouse prior to being transplanted (Plate 2.2 a and b). Seedlings were transplanted into the South field on 21 November 2022, while clones were transplanted into the East field on 22 November 2022 and into the North field on 28 November 2022. The crops were irrigated using dripper irrigation lines (Plate 2.3 a), with a dripper applied 0.05 m away from each plant stem to avoid stem rot (Plate 2.3 b). Fertigation was applied through the irrigation lines. Plants within rows were spaced approximately 2 m apart, while the row-spacing was approximately 2.5 m (Plate 2.3 c), leading to a low planting density of only 2 000 plants ha^{-1}. A low plant density was used to mitigate the spread of disease that had occurred during previous seasons. Every fifth row was left fallow and used as a tram line for tractors to move through when spraying (Plate 2.3 d). In the South field, after plants had grown over 1 m tall, they were 'topped', which involves removing their apex to slow the plant's vertical growth and encourage secondary branching. This is a management strategy that encourages a higher concentration of flowers to form before being harvested. The buds were harvested on 15 April 2023.

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Plate 2.2: (a) Hemp seedling germinated in a greenhouse; and (b) trays containing hemp seedlings

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Plate 2.3: (a) Experimental site containing hemp; (b) hemp plant with dripper 0.05 m away; (c) view from the top of the research tower looking from the South field towards the East field. Note both sapling and row spacing; and (d) hemp plants with research tower in the background

The underlying soil texture information was obtained using the Soil and Terrain Database (SOTER) for South Africa, an international database of information on soil and terrain properties (Batjes, 2004). The South African database was downloaded and imported into QGIS (version 3.28.11), where the soil category for the local farming business was determined. This soil category, within the SOTER database contained codes for their associated landform, lithology and soil texture that were matched according to Batjes (2004) and Dijkshoorn, van Engelen and Huting (2008). As such, the research site fell on soils that are well drained, with approximately 74% sand, 5% silt and 21% clay within the top 0.2 m of the soil profile and can therefore be considered as a sandy clay loam.

A field specific soil fertility analysis was conducted and the elements within the soil profile across the three fields are summarised in Table 2.1 with their corresponding reference locations (Figure 2.2).

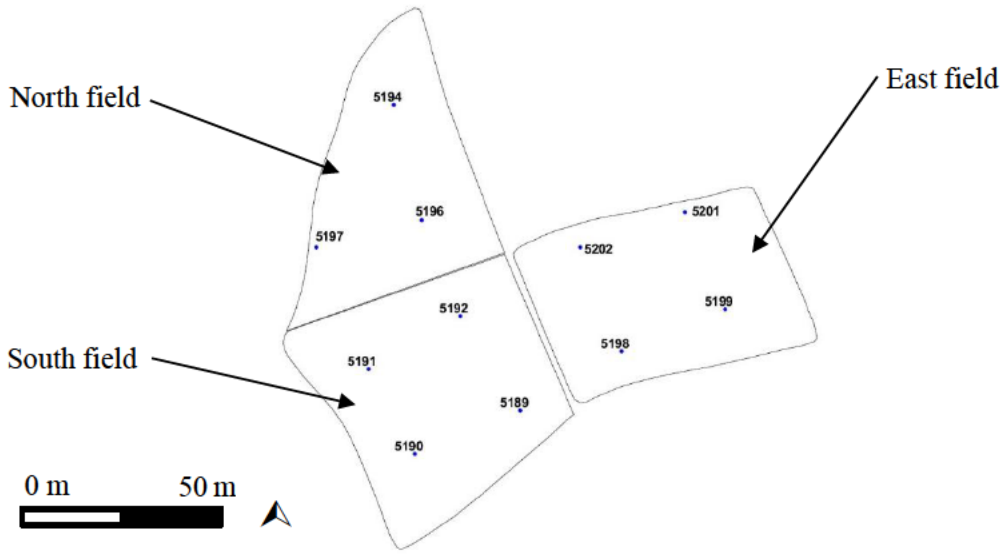


Figure 2.2: Location of soil sample reference numbers (source: Local farming business)

Table 2.1: Summary of soil elements across the three fields taken in August 2022 (source: local farming business)

Lab no	Reference no	pH	Pbray I	K	Na	Ca	Mg	Ex Acid KCL	%Ca	%Mg	%K	%Na	Acid Sat	Ca: Mg	(Ca+Mg)/K	Mg: K	S-Value	Na: K	CEC	Density	Sulphur	Zn	Mn	Cu	Fe
		-	mg/kg			mg/kg		cmol (+)/kg		%			%	1.5-4.5	10.0-20.0	3.0-4.0	cmol (+)/kg	-	cmol (+)/kg	g/cm3	mg/kg		mg/kg DTPA		
G30-40377	5189 (S)	5.5	28	366	26	2532	568		68.92	25.37	5.1	0.61		2.72	18.5	4.98	18.37	0.12	18.37	0.93	20.47				
G30-40378	5190 (S)	5.16	23	381	15	1854	467		65.57	27.08	6.88	0.47		2.42	13.46	3.93	14.14	0.07	14.14	0.97	13.92				
G30-40379	5191 (S)	4.63	26	231	17	1372	407		63.14	30.73	5.45	0.68		2.05	17.23	5.64	10.87	0.13	10.87	0.98	24.05				
G30-40380	5192 (S)	5.06	20	242	20	1789	527		64.02	30.92	4.44	0.62		2.07	21.39	6.97	13.97	0.14	13.97	0.96	14.55	3.94	46.18	3.24	89.37
G30-40382	5194 (N)	5.46	36	330	21	1868	518		64.34	29.23	5.82	0.62		2.2	16.09	5.03	14.52	0.11	14.52	0.99	9.84	3.44	38.86	2.78	68.99
G30-40384	5196 (N)	5.39	39	377	28	2037	480		66.96	25.89	6.34	0.8		2.59	14.64	4.08	15.21	0.13	15.21	1.03	11.09				
G30-40385	5197 (N)	4.84	22	271	38	1770	476		65.02	28.68	5.1	1.2		2.27	18.39	5.63	13.61	0.24	13.61	0.95	20.1				
G30-40386	5198 (E)	4.7	43	261	28	1533	449		63.16	30.35	5.49	1		2.08	17.02	5.53	12.13	0.18	12.13	1.02	39.96				
G30-40387	5199 (E)	5.12	35	201	24	1195	360		62.58	30.94	5.37	1.11		2.02	17.4	5.76	9.54	0.21	9.54	1.06	27.07	3.71	32.85	3.07	67.88
G30-40389	5201 (E)	4.53	51	258	26	1260	332		64.32	27.8	6.75	1.13		2.31	13.65	4.12	9.79	0.17	9.79	1.06	49.2				
G30-40390	5202 (E)	4.12	22	176	23	998	283		57.16	26.58	5.14	1.14		2.15	16.29	5.17	7.86	0.22	8.73	1.04	64.91				

2.3.2 *Field Equipment*

To determine total ET, an eddy covariance system (EC150 EasyFlux, Campbell Scientific, Logan, Utah, USA; Plate 2.4) was installed in the South field on a lattice mast, positioned in consideration of the dominant wind direction to optimize the fetch, ensuring at least 100 m of hemp crop in the upwind direction.

Plate 2.4: The 6 m tall eddy covariance system installed.

Net irradiance (CNR4, Kipp and Zonen, Delft, Netherlands) was measured on site above the canopy. To measure the flux of H_2O over the crop canopy, an open path gas analyser (EC150, Campbell Scientific, Logan, Utah, USA) and sonic anemometer (CSAT3A, Campbell Scientific, Logan, Utah, USA) were used (Plate 2.5). They were attached to the mast and maintained at a height of approximately 2 m above the average crop height. Latent Energy (Eqn. 2.1) was calculated as follows:

$$LE = \lambda \frac{M_w\, M_a}{\overline{P}}\, \overline{\rho}\, \overline{w'e'} \tag{2.1}$$

where LE was calculated by multiplying the latent heat of vaporisation (λ) by the ratio of molar masses of water and air, using water vapour pressure (e), wet air density ($\overline{P}$), atmospheric pressure ($\overline{\rho}$), and instantaneous wind speed (w). The standard coordinate rotations and corrections were applied on the datalogger (Campbell Scientific, 2018).

A fine wire (FW) thermocouple (FW1 Type E, Campbell Scientific, Logan, Utah, USA) with a diameter of 25 µm was attached to the CSAT3A for high frequency air temperature measurement. Rainfall was measured (TE525, Texas Instruments, Dallas, Texas, USA) and rainfall gaps over a period of 3 weeks, due to a blocked raingauge, were patched using rainfall data from a raingauge 16 km from the site, which had a similar daily rainfall (R^2 = 0.82). A temperature and relative humidity sensor (HC2S3, Campbell Scientific, Logan, Utah, USA) was placed in a radiation shield (41003-5, Campbell Scientific, Logan, Utah, USA) at a height of 2 m above the canopy. The EC150, FW, HC2S3 and CSAT3A measurements were sampled at a frequency of 10 Hz using a datalogger (CR3000, Campbell Scientific, Logan, Utah, USA) and averaged at 30-min timestamps. Instruments used are summarised in Table 2.2.

Volumetric Water Content (VWC) of the top 0.6 m of the soil profile was measured using three water content reflectometers (CS616, Campbell Scientific, Logan, Utah, USA), that were placed within the row but away from the dripper line points. The three reflectometers were placed at depths of 0.15 m, 0.3 m, and 0.6 m (Plate 2.6).

Plate 2.5: (a) Sensors including the CSAT3A, EC150 & FW1 attached together, (b) four component net radiometer.

Plate 2.6: Setup of Volumetric Water Content sensors.

Reference evapotranspiration (ETo) was calculated using the FAO-56 Penman-Monteith method (Allen *et al*. 2006). An hourly formula, including small night-time values, was used from data collected at the flux tower to obtain ETo and to determine a monthly crop coefficient. Plant LAI was measured (LAI-2200C, LI-COR, Inc, Nebraska, USA) by walking a straight line perpendicular to the plant rows, alternating readings between directly beneath the plants within the rows, and between plants along the rows. This method was chosen to ensure full coverage of the field while minimizing labour and time constraints. Every first and fifth sample were taken above the canopy, with the second, third and fourth samples taken below the canopy. Plant dimensions were measured using a plastic measuring pole.

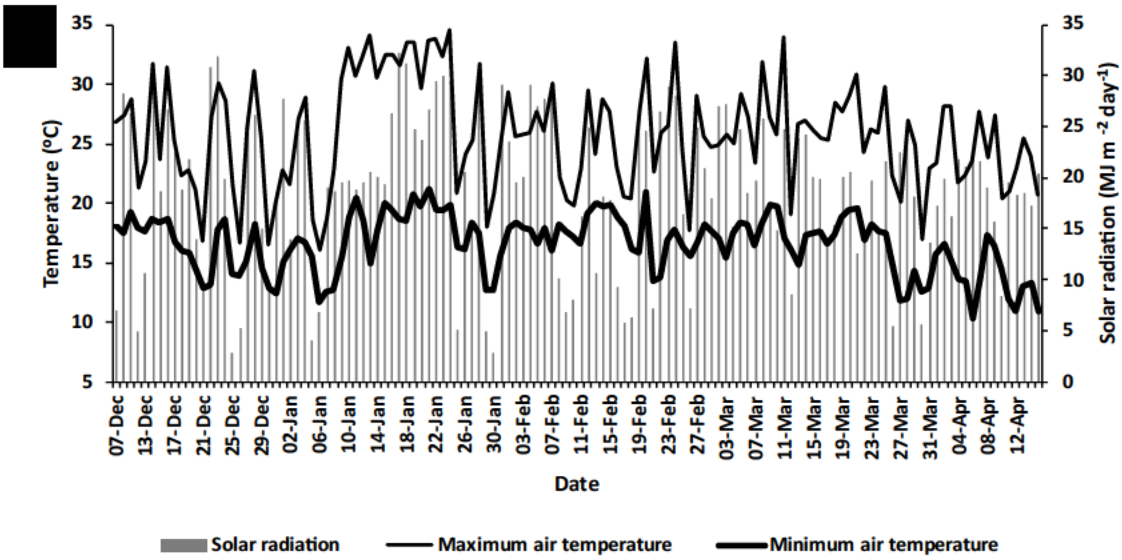
Table 2.2: Instruments included in the eddy covariance system.

Instrument	Measurement	Manufacturer
CS616 Water Content Reflectometers	Volumetric soil water content	Campbell Scientific, Logan, Utah, USA
EC150 CO_2/$H_2$0 Open-Path Gas Analyser	CO_2/$H_2$0 flux	Campbell Scientific, Logan, Utah, USA
HFP01 Soil Heat Flux Plate	Ground heat flux	Huxaflux, Delft, Netherlands
CSAT3A Three-Dimensional Sonic Anemometer	CO_2/$H_2$0 flux	Campbell Scientific, Logan, Utah, USA
TE525mm Tipping Bucket Rain Gauge	Rainfall	Texas Instruments, Dallas, Texas, USA
HC2S3 Temperature and Relative Humidity Probe	Temperature; relative humidity	Campbell Scientific, Logan, Utah, USA
CNR4 Net Radiometer	Net solar radiation	Kipp and Zonen, Delft, Netherlands
FW1 Type E fine wire thermocouples	Air temperature	Campbell Scientific, Logan, Utah, USA
TCAV Type E thermocouples	Average soil temperature	Campbell Scientific, Logan, Utah, USA
LAI 2200C Plant Canopy Analyser	Leaf Area Index	LI-COR, Inc, Nebraska, USA

2.4 Results

The average temperature over the growing season was 20.3^{o}C (Figure 2.3 a), with a minimum air temperature of 10.2^{o}C and maximum of 35.6^{o}C occurring due to high incoming shortwave radiation. A period of high temperatures were observed in January 2023 with maximum daily temperatures remaining above 30^{o}C for a two-week period. A gradual trend of decreasing minimum temperature associated with decreasing solar radiation was observed towards the end of the summer season, with April having the lowest monthly average temperature over the season (17.8^{o}C). Throughout the growing season, daily solar radiation averaged 13.5 MJ m^{-2} day^{-1}, with April having the lowest monthly average solar radiation (12.9 MJ m^{-2} day^{-1}).

The average daily wind speed fluctuated between 2.2 m s^{-1} in the first half of the season, and 1.8 m s^{-1} in the second half (Figure 2.3 b). Storms occurred on 20 February, where high wind speeds reached 3.4 m s^{-1}, with a corresponding shift in wind direction from South-South-West to East-North-East. Daily average wind speed gradually decreased from planting in December to harvest in April, associated with a seasonal transition from mid-summer into autumn. The daily vector average wind direction was approximately 200^{o} or from the south-south-west in which there was approximately a fetch of 105 m over the hemp crop.



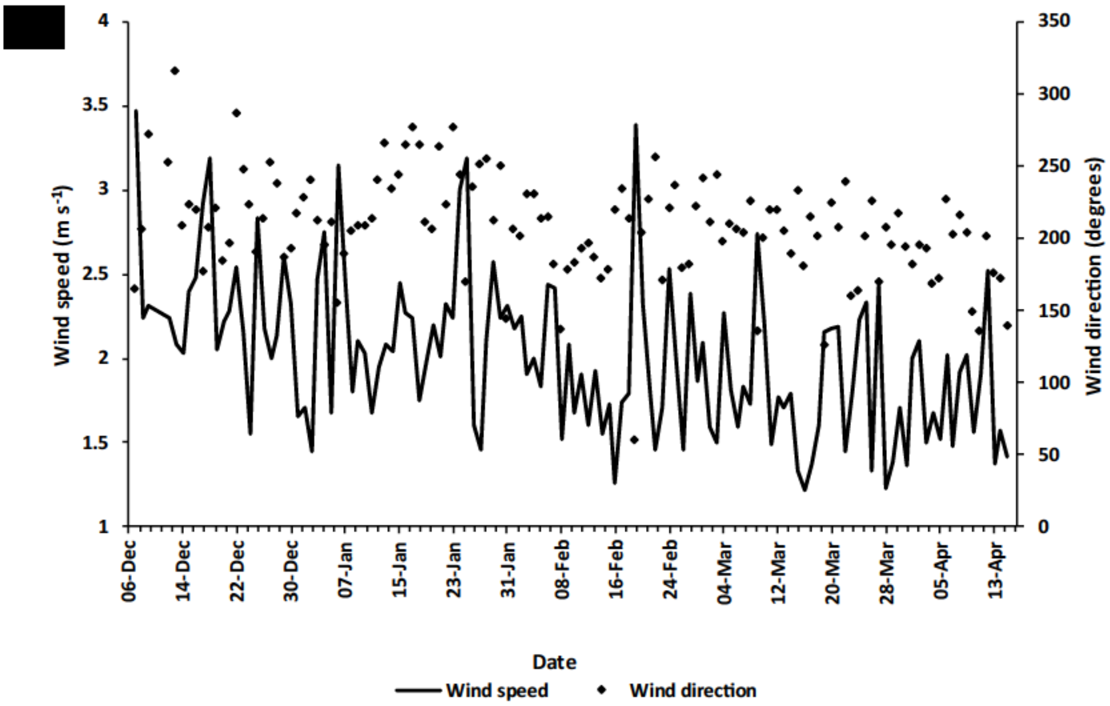


Figure 2.3: (a) Minimum and maximum air temperature and solar radiation; and (b) average daily wind speed and direction between December 2022 and April 2023

The first six days of daily rainfall in December were not measured as the eddy covariance system was installed on 7 December 2022, yet December had the highest monthly rainfall (204 mm) over the growing season and April had the lowest (23.6 mm). As the crop was harvested halfway through the month (15 April 2023), only half a month of rainfall data were collected. The highest daily rainfall (35 mm) occurred on 29 December (Figure 2.4 a). A dry period was observed between 8 and 26 January, where no precipitation occurred. The total rainfall over the growing season was 452 mm.

Drip irrigation was applied throughout the growing season (Figure 2.4 b). The soil water content was monitored using an AquaCheck soil moisture probe, and irrigation was applied accordingly. No irrigation was applied during the months of December due to sufficient rainfall. Irrigation applied was highest in March, totalling 15 L plant^{-1} month^{-1} (1.56 mm plant^{-1} month^{-1}), followed by January (13.8 L plant^{-1} month^{-1} or 1.4 mm plant^{-1} month^{-1}), February (8.1 L plant^{-1} month^{-1} or 0.8 mm plant^{-1} month^{-1}), with April requiring the least irrigation with only (6 L plant^{-1} month^{-1} or 0.6 mm plant^{-1} month^{-1}).

The volumetric water content throughout the soil profile (measured at 0.15 m, 0.3 m and 0.6 m) was calculated to represent the profile as a whole down to 0.6 m (Figure 2.4 c), which represents the rooting zone. The VWC fluctuated between 20% to 40%, corresponding with rainfall events, throughout the growing season. An increase in VWC (20% to 35%) occurred towards the end of December, due to high rainfall, before decreasing to 15%, at harvest, in April.

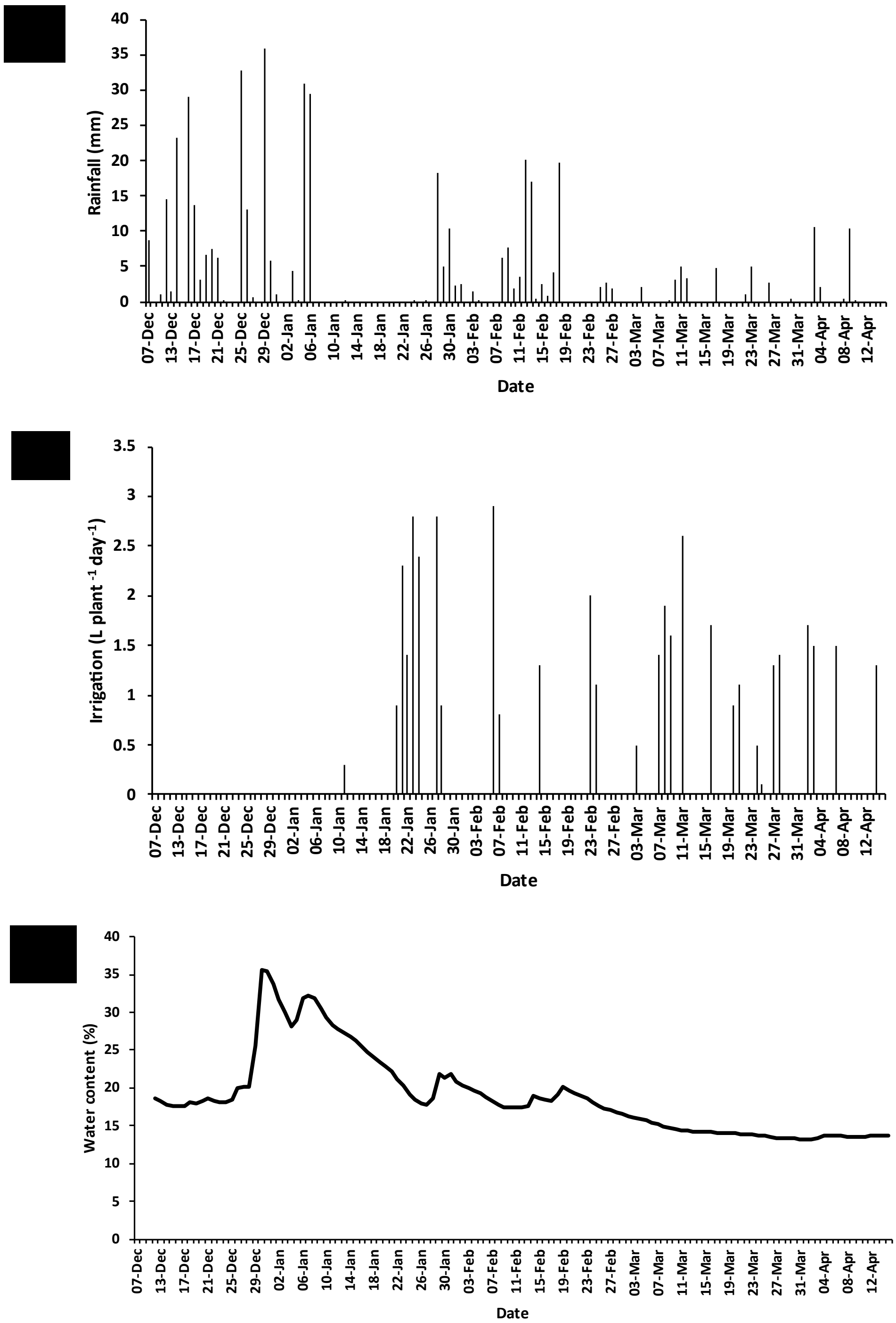


Figure 2.4: (a) Daily rainfall; (b) irrigation applied over the growing season; and (c) average volumetric water content throughout the soil profile between December 2022 and April 2023

The average daily ET over the measurement period was 2.9 mm (Figure 2.5) with a maximum of 6.9 mm. High variability in ET values were observed between December and March, due to fluctuations in weather conditions (Figure 2.3 a), with values stabilizing and dropping as autumn progressed. Days with higher ET corresponded to hot, dry periods such as 9 to 12 January (remaining between 5 mm day^{-1} and 6 mm day^{-1}) and 20 February 2023 (7 mm day^{-1}). A summer thunderstorm occurred on 30 January with high wind speeds and hail, incurring damage (Plate 2.7), broken branches and lodging of plants, with plant stems remaining bent over. The average water required to grow a hemp tree in the South field was 28.4 L $tree^{-1}$ day^{-1} (2.94 mm $plant^{-1}$ day^{-1}). This includes the water used by the weeds and that evaporated from the soil surface area around each plant which cannot be excluded from the water use of the crop in a field setting.

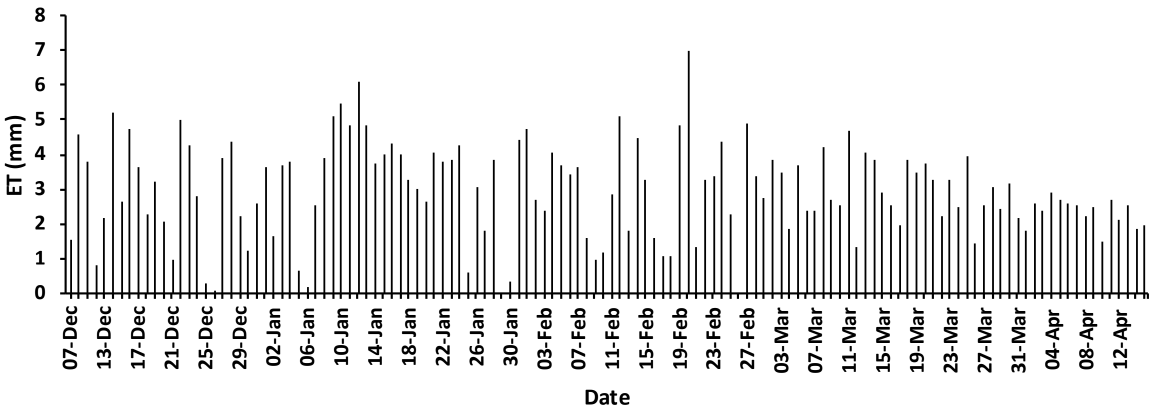


Figure 2.5: Daily evapotranspiration between December 2022 and April 2023, measured using eddy covariance technique

Plate 2.7: Damaged and broken plants, on 30 January 2023, due to hail

Due to the location of the eddy covariance system and the predominant wind direction being from the south (Figure 2.3 b), the area contributing to the measurements was primarily the South field. Plant dimensions and LAI were therefore recorded for the South field. However, to showcase the difference between genetic variation of seedlings and clones, the plant diameters and LAI of the North field (clones) were included as a comparison to the South field (seedlings). The measurement of plant diameter and LAI began on growing day 24, after the seedlings had been established, but the x-axis in Figure 2.6 a, b and c starts from growing day 20 to provide a clearer visual representation. In a comparison of LAI, height and width of plant canopy between the North and South fields (Figure 2.6 a, b, c), the earliest measurements of LAI (Figure 2.6 a) included weeds, which were removed during the early growth of the crop. This leads to an overestimation of LAI-values particularly early in the growing season. This is supported by the decrease in LAI from growing day 24 to 36 (North field), and the growing day 38 to 50 (South field). Once in the rapid growth phase, the LAI increased from 0.5 to 0.9 for both fields over a period of approximately six weeks. The South field LAI was higher than that of the North field in January (0.59 and 0.52, respectively) but slightly lower by the end of February (0.87 and 0.89, respectively).

The South field plants (seedlings) were consistently taller than the North field plants (clones; Figure 2.6 b), and reached a height of 1 600 mm, while the North field plants reached a maximum height of 800 mm at the time of last measurement. If this is extrapolated to harvest, it suggests a final height of approximately 1 000 mm, still less than the canopy height of the South field plants.

The plant canopy width increased over time, with the South field plants consistently measuring higher aerial canopy cover than the North field plants (Figure 2.6 c). The largest increase in plant canopy width was observed in the South field, where it grew from 766 mm on day 50 to 1 284 mm on day 73. The North field showed similar growth from 538 mm on day 59 to 985 mm on day 81. The final canopy diameter of the hemp canopy in the South field was 1 500 mm, while the North field plants were 1 000 mm.

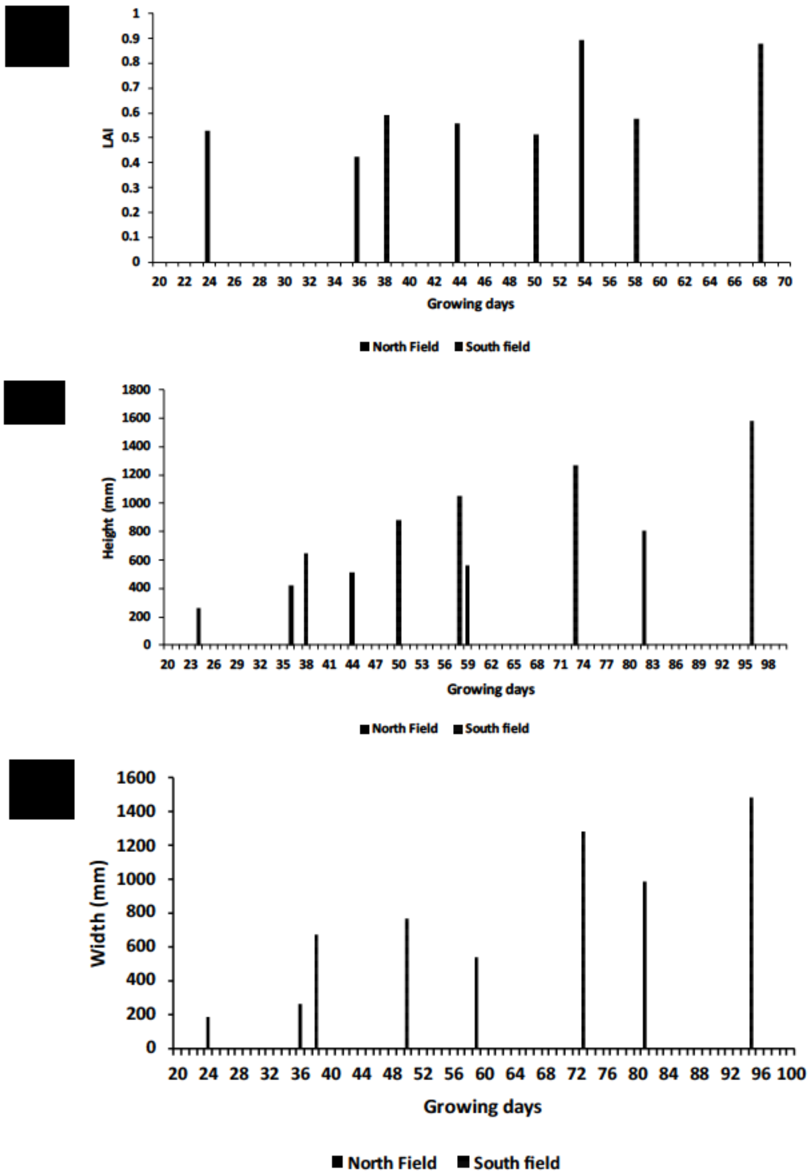


Figure 2.6: (a) LAI of hemp plants; (b) plant height of South field and North field over the growing season; and (c) plant width of North and South field crops over the growing season

Reference evapotranspiration in December and January fluctuated due to variations in weather conditions in the summer rainfall area. High ETo values were observed in mid-January (Figure 2.7 a), peaking at 7.2 mm on 24 January. These higher values correspond with a period of clear skies (Figure 2.3 a) and no rainfall (Figure 2.4 a). Daily average ETo values were lower but more consistent during the month of April compared to December and January, due to the onset of autumn, with lower, but more consistent daily solar irradiance (Figure 2.3 a).

The flux footprint represents the distance from the research tower where maximum evapotranspiration occurs and is calculated by the EC program, using a complex mathematical algorithm. The distance of maximum contribution to measurements remained typically within 20 m to 50 m from the research tower (Figure 2.7 b), until April 2023 where the daily flux footprint variability increased. This was in part due to raising the height of the EC system sensors at the beginning of April from 2.8 m to 3.3 m above the soil surface, to keep it approximately 2 m above the crop canopy to accommodate plant growth, as recommended by international literature (Burba, 2021). Although the distance of maximum contribution to flux measurements increased, there was a sufficient fetch of hemp crop to ensure that this did not affect ET measurements. The maximum distance of upwind contribution to the flux footprint indicates that the majority of the flux measurements were derived from the hemp crop or the South field.

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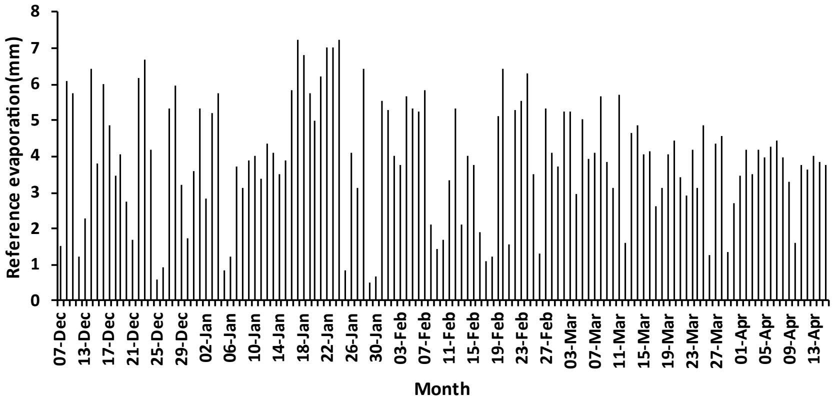

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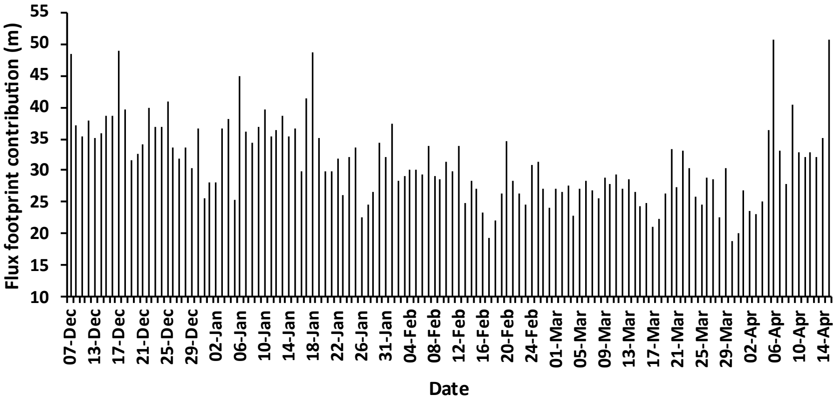

Figure 2.7: (a) Reference evaporation of the hemp crop between December and April; and (b) distance from the research tower that had the maximum effect on evapotranspiration estimates

The monthly crop coefficient (Figure 2.8 a) increased from planting in December (0.69) to a peak in March (0.76). The crop coefficient was lower in April (0.63). Harvest took place on 15 April 2023, and as such only half a month of data was collected for April, potentially causing a slight underestimation of measurement. The average crop coefficient over the season was 0.72.

The North field, containing clones, produced a higher bud yield of 6 359 kg ha^{-1} at the time of harvest (Figure 2.8 b), whilst the South field bud yield was lower, at 3 623 kg ha^{-1}. The clones (North field) had a higher overall yield compared to that of the seedlings (South field) as the plant density of the South field at harvest was 1 035 plants ha^{-1}, while the North field had a harvest density of 2 000 plants ha^{-1}. Although both fields had an initial planting density of 2 000

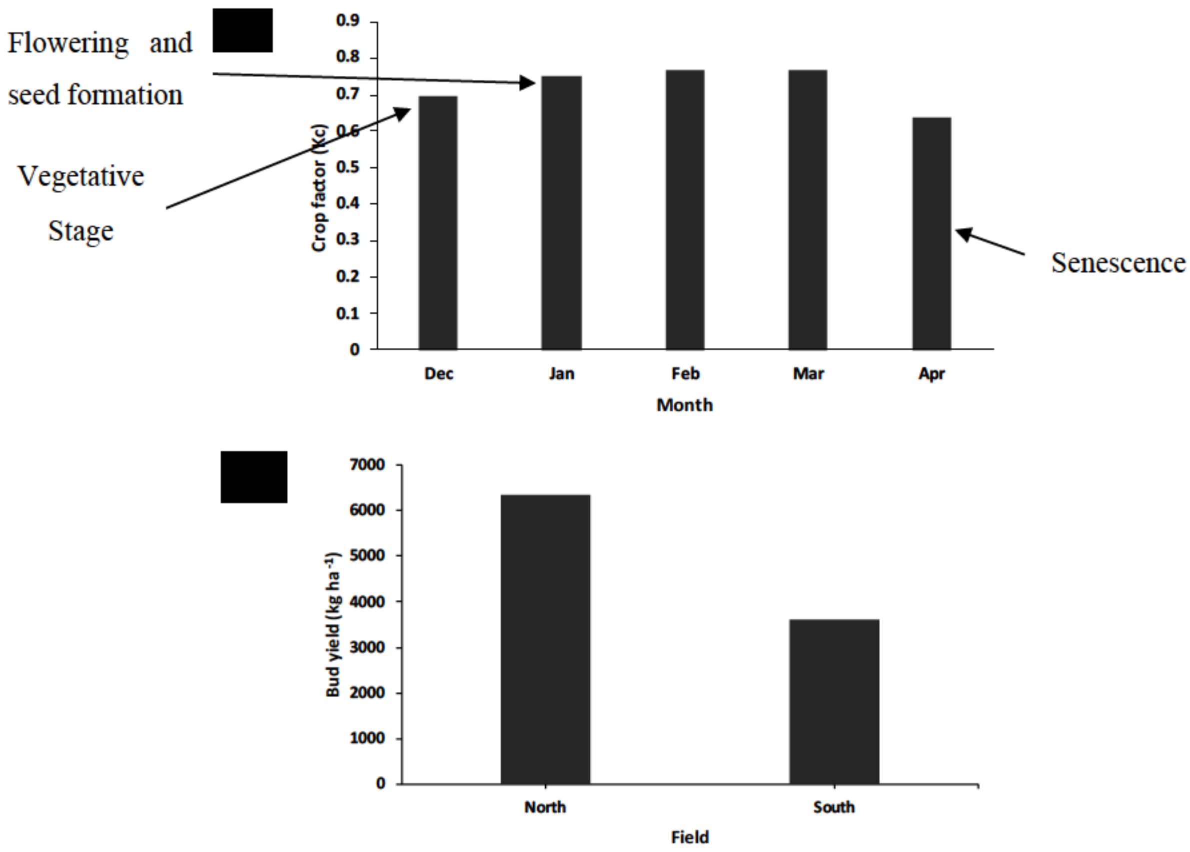

Figure 2.8: (a) Monthly crop coefficient of hemp; (b) total bud yield per hectare harvested at the end of the growing season

plants ha^{-1}, the South field density was almost half that of the North field at time of harvest due to the removal of male hemp plants that needed to be removed to prevent cross-pollination. This significant difference in plant density, size and yield highlights the importance of planting strategy and seed or shoot stock used in hemp farming.

The water productivity (WP), which requires measurement of ET, was calculated for the South field, as the research tower was placed within that field, with the flux footprint obtained primarily from this field. The WP of the South field plants represent the mass of bud produced per cubic metre of water lost to ET and was found to be 0.96 kg m^{-3}.

2.5 Discussion

The daily ET fluctuated from planting in November until March, due to the high variability in daily temperatures, solar irradiance, and rainfall, after which it was more stable. Comparative studies report daily water consumption as a synonym for daily ET (Cosentino *et al*. 2013; Thevs and Aliev, 2022; Thevs and Nowotny, 2023), however, Cosentino *et al*. (2013) calculated crop water use, rather than ET, by measuring irrigation, precipitation, and gravimetric soil water content before and after each irrigation event. Thevs and Aliev (2022) used sapflow measurements to calculate hemp ET, while Thevs and Nowotny (2023) used remote sensing techniques (Simplified Surface Energy Balance Index (S-SEBI) model) to estimate crop ET. The total ET of the hemp crop in the present study was 377 mm over the growing season (Figure 2.5), which is similar to that recorded by Thevs and Aliev (2022), who observed an ET of 353 mm over the growing season in northern Kazakhstan, for the hemp variety Santina 70. However, Thevs and Aliev (2022) used sapflow measurements, which measures hemp transpiration and does not include surrounding weeds, as was the case in the present study. Sapflow and EC measurements have different strengths and limitations, and neither method should be considered better than the other. For example, sapflow measurements do not account for evaporation from soil and canopy interception, and therefore do not represent total ET (Wilson *et al*. 2001). Evapotranspiration in the present study was similar to the findings of Thevs and Nowotny (2023), who observed an average of 343 mm ET over a four-year trial (April-October annually; 2018-2021) in northern Germany, with the study's highest annual ET of 407 mm occurring in 2019. Cosentino *et al*. (2013) found a water use of 327 mm for the hemp variety Futura 75 in southern Italy, but this was not a direct measurement of ET. In the present study, ET of the hemp crop peaked in mid-February at 6.9 mm day^{-1}, before decreasing steadily until harvest, which is similar to Thevs and Nowotny (2023), who observed a peak ET of 6 mm day^{-1} after which ET steadily decreased until harvest. Although Cosentino *et al*. (2013), Thevs and Aliev (2022), and Thevs and Nowotny (2023) all utilised a completely different approach to the present study, they had comparable temperature regimes during the growing season (15^{o}C to 20^{o}C). However, Cosentino *et al*. (2013) and Thevs and Aliev (2022) both utilised drip irrigation, while Thevs and Nowotny (2023) did not apply irrigation at all.

Rainfall over the study site totalled 452 mm over the growing period (Figure 2.4 a) and was higher than evapotranspiration (377 mm), with December having the highest monthly rainfall (204 mm) and April having the lowest (24 mm). According to Struik *et al*. (2000) the marketable value for non-irrigated hemp drops drastically when precipitation drops below 300 mm by placing the plant under water stressed conditions. The period of 8 to 26 January had large rainfall gaps in which irrigation took place when required (Figure 2.4 b). As a result, the VWC within the top 0.6 m of the soil profile was relatively high throughout the soil profile (Figure 2.4 c), ensuring the prevention of water-stressed conditions. Excess rainfall at the beginning of the growth season corresponded with the increase in VWC in January (up to 35%), before maintaining a VWC of 15% between March and April. It should be noted that these results are for a well-watered crop that did not experience water stress.

Sufficient fetch is commonly a challenge with EC measurements. The maximum flux footprint represents the distance from the research tower where the maximum influence on ET originates. The maximum flux footprint was observed to remain between 20 m to 50 m from the research tower (Figure 2.7 b) until April 2023, where the flux footprint increased with higher daily variability occurring. There was no noticeable change in the average wind speed over this period (Figure 2.3 b), and therefore footprint variability is likely due, in part, to the raising of the height of the EC system sensors from 2.8 m to 3.3 m above the soil surface at the beginning of April, to keep it approximately 2 m above the crop canopy to accommodate plant growth as recommended by Burba (2021) for all crop types. Flux footprint is influenced by instrumentation height, canopy height, wind speed, friction velocity, thermal stability, surface roughness and zero-plane displacement (Schuepp *et al*. 1990; Burba, 2021). The maximum flux footprint extent increases with increased sensor height, while the magnitude of the peak contribution is reduced. The surface roughness coefficient would have increased as the plant height increased, and this could have affected the flux footprint. In this research the daily vector average wind direction was approximately 200^{o}, or from the south-south-west, in which there is approximately a fetch of 105 m over the hemp crop. As a result, it was concluded that there was negligible influence of both the North and East fields (clones) on ET estimates of hemp due to the wind direction, and that the ET estimates were representative of the South field (seedlings). The daily average wind speed over the hemp crop in the first half of the growing season was 2.2 m s^{-1} (Figure 2.3 b), while the second half of the growing season averaged 1.8 m s^{-1} as autumn set in. Some high wind speeds were observed (Figure 2.3 b) and there was lodging of plants (bending of stems near ground level) and hail damage (Plate 2.7), particularly those grown from seedlings in the South field, due to their larger size.

In the present study, the LAI of both the North and South fields were measured, including weeds between hemp plants. The isolation of hemp plants, and thus isolated LAI measurements, did not take place as surrounding weeds and soil surfaces are naturally found in commercial cultivation areas, adding to the water consumption of the field. The LAI was much lower in comparison to previously reported values (Tang *et al*. 2018; Herppich *et al*. 2020), and declined in the early stages of the season with the North field declining from 0.52 to 0.42 between the 24^{th} and 36^{th} growing day, while the South field declined from 0.6 to 0.51 during the 38^{th} to 50^{th} growing day (Figure 2.6 a). This is because the earliest measurements of LAI included weeds, which were removed at times, leading to the overestimation of initial values. The initial drop in LAI in both fields could be attributed to the removal of these weeds between the rows. The low LAI of the South field was also impacted by the removal of male hemp plants which were removed to prevent cross pollination with the female hemp flowers and influence the chemical constituents of the bud yield (Malabadi *et al*. 2023). This caused the plant density to almost halve. Although the utilisation of feminized seed encourages the growth of strictly female plants, the occurrence of males is still possible.

Feminized seed is created through the application of colloidal silver or gibberellic acid to female hemp plants, inducing the formation of male flowers on these plants (Owen *et al*. 2023). The resulting pollination of another female hemp plant leads to the formation of seed with female chromosomes only, effectively eliminating male genetics. However, this does not guarantee a 100% success rate (Owen *et al*. 2023), as seen in this study. This is emphasised by the fact that only the South field, containing seedlings, had the occurrence of male hemp plants, whereas the North field, containing clones, did not. In the present study, the harvest density of the North field was 2 000 plants ha^{-1} (in-row spacing of 2 m, inter-row spacing of 2.5 m), while the harvest density of the South field was low, at 1 035 plants ha^{-1} due to the removal of male hemp plants. The North field therefore had a higher bud yield per hectare (6 359 kg ha^{-1}; Figure 2.8 b) than the South field (3 623 kg ha^{-1}). According to a report by Institute for Economic Justice (2023), dry bud for medical cannabis sold at wholesale at approximately ZAR37.4 - ZAR74.8 per gram at the time of writing. Plant height and width of the South field increased quicker than the North field between January and February (Figure 2.6 b and c) due to the removal of male plants, leading to less competition for light, water and nutrients and more space between plants to grow, which in turn increased the risk of lodging. Furthermore, in the present study, plants were ‘topped’ to encourage lateral growth, additional branching out of the plant and to encourage higher concentrations of flowers to form before harvest.

Water use efficiency (WUE) and WP are internationally accepted agricultural terms, yet there has been a lack of naming consistency in their usage (Sadras *et al*. 2012). WUE expresses the ratio at which the input of water in the agricultural system reaches the target crop, while WP expresses the water used by the crop compared to the plant biomass produced (Kilemo, 2022). WUE is often incorrectly expressed as the rate of biomass production to water consumed. More specifically, the water productivity of a plant is defined as the harvested plant yield compared to the amount of water consumed (Delauney and Verma, 1993; Herppich *et al*. 2020), or as the ratio of net CO_2 assimilation rate to transpiration (Lamaoui *et al*. 2018). A review of the WP values of various crops by Zwart and Bastiaanssen (2004) indicate that it can vary, depending on factors such as climate, irrigation management and soil management. For example, Pejic *et al*. (2018) cited a number of global studies that indicate hemp WP values differ greatly from place to place, although the study's sources were either not peer-reviewed or were inaccessible and could therefore not be verified. Furthermore, the few reports that do exist on the WP of hemp are difficult to compare since different bases of comparison (bark yield, biomass production, stem dry weight) were used to calculate the WP of the crop (Lisson and Mendham, 1998; Di Bari *et al*. 2004; Cosentino *et al*. 2013). Previous studies have tended to focus on hemp production for different reasons, such as fibre (Cosentino *et al*. 2013; Tang *et al*. 2016, 2022), stem (Tang *et al*. 2017) and seed (Tang *et al*. 2016, 2017), whereas the present study utilised hemp bud production for medicinal purposes. WP can be increased by simply using lower irrigation techniques (Babaei & Ajdanian, 2020), particularly in arid areas. It has been reported that hemp WP does not change under water deficit stress (Gill *et al*. 2022), however this conflicts with results by Cosentino *et al*. (2013), who determined that the WP values of hemp, under non-stressed conditions in a semi-arid Mediterranean environment, was lower compared to the WP of the same crop under water-stressed conditions.

WP values are often influenced by an over-estimation of water transpired by the crop (Cosentino *et al*. 2007). A study by Cosentino *et al*. (2013) found that hemp has a WP of 2.73 kg m^{-3} under non-water-stressed conditions in a semi-arid Mediterranean environment. In the present study the WP of 0.96 kg m^{-3} over the growing season was significantly lower. The present study only considered the bud yield weight (Figure 2.8 b), while Cosentino *et al*. (2013) considered above-ground biomass of the whole plant at harvest. In addition, different management practices are used in the present study (such as topping), depending on the plants' intended use. This is undesirable in bark yield analyses, biomass production and stem dry weight as it causes the hemp plants to remain shorter and shortens the length of plant fibres within the stem (van der Werf *et al*. 1995). The result is that WP values between studies cannot be compared. It must be noted, however, that the ET used in the derivation of WP in this study includes the ET from the surrounding soil surface and grasses or weeds. This is justified as the presence of bare soil or growth of weeds is unavoidable in commercial cultivation (unless under certain circumstances, such as the surface being covered by plastic sheeting, often not cost effective).

Many crops have prescribed Kc values, that are readily available (Allen *et al*. 1998). There are, however, only a limited number of studies that provide Kc values for hemp. Studies by Cosentino *et al*. (2013); Garcia Tejero *et al*. (2014); Pejic *et al*. (2018); and Bajić *et al*. (2022) used Kc with a reference evaporation to estimate water use. Some studies by Nougabil, Shahidi and Hamami (2019); Thevs and Aliev (2022), and Thevs and Nowotny (2023) measured evapotranspiration and calculated Kc for their own trials (located in Iran, northern Kazakhstan and north-east Germany, respectively). In the present study, monthly Kc was calculated through the ratio of ET to ETo. Initial values in December were 0.69, reaching 0.76 between the months of January to March (Figure 2.8 a), before lowering to 0.63 at harvest in April. The vegetative growth stage (0.69), flowering and seed formation (0.76), and senescence stages of growth (0.63) can be seen. The crop coefficient was higher than expected in the first two months of the trial when the hemp plants were small. This is likely due to the rapid growth of weeds, where weeds were bigger than the hemp plants at times until they were removed. After full development of the canopy, from February until harvest in April, the ET estimates and Kc values were more representative of the hemp than the surrounding weeds and soil surface, due to the larger size of the hemp plants than surrounding vegetation, and the periodic removal of this vegetation. In the present study, a decline was observed in the month of April, where Kc dropped to 0.63. This is partly due to the onset of crop senescence but also partly due to an underestimation taking place, as half a month of measurements took place in April before harvest. These Kc are similar to the results of Thevs and Aliev (2022), whose calculated Kc peaked at 0.7 during their growing season in northern Kazakhstan.

The results of this study determined that the overall water usage was approximately 28.4 L plant^{-1} day^{-1} (2.94 mm plant^{-1} day^{-1}). This is similar to values published by Humboldt County Outdoor Medical Cannabis Ordinance Draft, 2010, in Bauer *et al.* (2015) that *Cannabis sativa*

L. plants use approximately 22.7 L plant^{-1} day^{-1} in north-western California, however this citation by Bauer *et al*. (2015) was unattainable by this study. It is further noted by Bauer *et al*. (2015) that ET data of hemp is limited in the published literature.

Limitations faced during the research included a lack of scientifically based information relating to *C. sativa* L., a high percentage of male plants in the South field (seedlings), and lodging of large seedling plants. Further research on the wider hydrological impacts and streamflow reduction associated with the cultivation of hemp will enhance our understanding of this versatile crop, its environmental impact, and its economic feasibility.

2.6 Conclusions

There is a global interest in the expansion of areas planted under hemp, however there is relatively little information on water-use and productivity of hemp for decision makers to base their strategies of expansion upon. This is particularly important in water-deficit countries and those replacing existing food crops with hemp. This study provides the first water-use and productivity measurements of hemp grown in South Africa. The water-use over the growing season was higher than comparative studies, and the water productivity of 0.96 kg m^{-3} was lower than other results reported. The crop coefficient derived in this study agrees with international studies and provides a benchmark for estimating water use of hemp across diverse climatic areas. The crop coefficient is used in many hydrological models and will enable the assessment of hemp as a streamflow reduction activity in South Africa. The planting density typically used in South Africa was lower than that of international studies. This is significant because the many different uses of the hemp plant lead to different parts of the plant being assessed in terms of WP. A further understanding of the comparison of water productivity to economic productivity, in terms of the water used relative to the rand value of yield produced in South Africa, would benefit growers.

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CHAPTER THREE

MODELLING EVAPOTRANSPIRATION OF *Cannabis sativa* L., KWAZULU-NATAL MIDLANDS, SOUTH AFRICA.

3.1 Abstract

Few of the energy balance models that estimate evapotranspiration (ET) have been used to model a hemp crop, and where crop modelling of hemp has been undertaken, it was primarily to address crop phenology or photosynthesis rather than ET. QWaterModel was chosen for this study to determine ET due to its operational simplicity, minimal input requirements and it is an open-source model. QWaterModel analysed thermal images acquired from an Unmanned Aerial Vehicle (UAV) over a single growing period of hemp in KwaZulu-Natal, South Africa. The QWaterModel estimates of ET (ET_{QW}) were compared to eddy covariance ET (ET_{EC}) results collected over the same period. A total ET_{QW} of 24.2 mm was modelled over five days when flights were performed throughout the season, while the EC system measured 16.9 mm over the same five-day period. ET_{QW} was highly variable across the field, due to a lack of canopy closure and elevation differences. The lack of canopy closure was due to a low planting density and became particularly evident after the removal of male plants during the growing season. ET_{QW} variation corresponded well with Normalized Difference Vegetation Index (NDVI), however ET_{QW} estimates at the beginning of the season, and after harvest, were more representative of the surrounding soil surfaces and grass cover than the hemp plants. This research provides the first remotely sensed ET estimates of hemp and underscores the fact that while QWaterModel provided valuable insights, a dual-source model would likely have offered better ET estimation by differentiating between plant and soil surfaces.

3.2 Introduction

Cannabis sativa L. can be used as medicine, fibre, food, or fuel in a diverse array of industries (Adesina *et al*. 2020), and has environmental benefits, being applied in fields of study such as phytoremediation and carbon sequestration. The ET of *Cannabis sativa* L., however, remains largely unknown (Ashworth and Vizuete, 2017), with few water-use estimates available in international literature, although it has been referred to as a water thirsty crop (Ashworth & Vizuete, 2017). Bauer *et al*. (2015) stated that a single *C. sativa* L. plant uses approximately

22.7 L of water a day over a growing season in California, USA (Humboldt County Outdoor Medical Cannabis Ordinance Draft, 2010, in Bauer *et al.* (2015)). *Cannabis sativa* L. can be sub-divided into two subspecies depending on their chemical composition. This ultimately affects the use of the plant. If the delta-9-tetrahydrocannabinol (THC) content of the plant is less than 0.3%, the plant is classified as 'hemp', if the THC content exceeds 0.3% the plant is classified as 'marijuana' (Wimalasiri *et al*. 2021). THC is the primary psychoactive compound in cannabis that binds to receptors in the brain and inhibit neurotransmitter release (Howlett *et al.* 2002). The effects of THC include euphoria, altered perceptions, increased appetite, and decline in cognitive abilities (Bally, Zullino and Aubry, 2014).

Evapotranspiration is described as the loss of water from the earth's atmosphere through the combined processes of evaporation from bare soil, open water bodies and plant surfaces, and transpiration from any organic material containing moisture (Li *et al*. 2009). It is the most important flux component of the water cycle within arid or semi-arid regions (Oki & Kanae, 2006). However, the direct measurement of ET, at a high temporal resolution using EC methods can be time consuming and expensive (Brenner *et al*. 2017), and is constricted to a limited flux footprint (Burba, 2021). Since the process of ET estimation depends on site-specific soil, hydrological, plant-physiological, and meteorological variables, many uncertainties in measurements can occur (Blatchford *et al*. 2019). As a result, the use of UAVs has increased as a cost-effective way to calculate ET (Brenner *et al*. 2018; Nisa *et al*. 2021), and involves the process of acquiring thermal images using a UAV, processing, and importing resultant images into a model. This method involves the use of remotely sensed thermal data with computer models to simulate ET fluxes at the earth's surface (Nisa *et al*. 2021). There exist various single-source models, such as SEBS, METRIC, SEBAL and QWaterModel (Ellsaßer *et al*. 2020; Nisa *et al*. 2021) that have relatively low model complexity and simple parameterization schemes to simulate turbulent fluxes; however, these are generally less accurate than dual-source models (such as TSEB and ALEXI) in determining thermal fluxes (Kustas & Norman, 1999; Verhoef *et al*. 1997). However, dual-source models are more complex, require technical expertise, and often require additional input parameters that are usually unavailable, hindering the application of these models (Ellsaßer *et al*. 2020). Single-source and dual-source models are differentiated by the fact that a single-source model treats the surface as a single, homogenous entity with a closed canopy cover, while dual source models partition fluxes between the soil surface and vegetating cover (Hoffmann *et al*. 2016; Xia *et al*. 2016). Some of the most commonly used single-source models available have been reviewed by Thevs and Nowotny (2023). Although the applications of remote sensing activities have increased in recent years, there is still a lack of modelling applications involving the ET of hemp, as more recent studies utilizing remote sensing techniques have focused on hemp phenology (Cosentino *et al*. 2012) or photosynthesis (Tang *et al*. 2018).

One such remote sensing model, QWaterModel, an open-sourced single-source energy model (Ellsaßer *et al.* 2020), is a modification from the DATTUTDUT (Deriving Atmospheric Turbulent Transport Useful To Dummies Using Temperature) model (Timmermans *et al*. 2015), that was modified to compensate for the occurrence of cloudy conditions, as the latter model can only be used in clear conditions. Bulusu *et al.* (2023) utilised the DATTUTDUT model in a tropical rainforest in Sumatra, Indonesia, by applying the QWaterModel, which is the DATTUTDUT model with a graphical user interface. The DATTUTDUT model performed well across two studies in tropical oil palm plantations in Sumatra, Indonesia (Ellsäßer *et al.* 2020, 2021), over vineyards in USA (Xia *et al*. 2016) and grasslands in Germany (Brenner *et al.* 2018). QWaterModel assumes that ET is low when high leaf surface temperatures are measured (hot pixels), and ET is high when cooler leaf surface temperatures are measured (cold pixels; Ellsaßer *et al.* 2020). Simply put, the model calculates ET_{QW} by using a set of parameters and sun-earth geometrics to solve the radiation budget (Timmermans *et al.* 2015) and produce an evaporative fraction (EF) that is scaled between the hottest pixels (zero ET) and coldest pixels (maximum ET) in the image, known as the wet and dry limit, which is used in the upscaling of hourly ET to daily ET. The QWaterModel was selected to estimate ET to demonstrate its applicability in assessing the spatial variability of ET over a new crop type (*Cannabis sativa* L.) due to its operational simplicity. An EC system at the site over the same period provided improved inputs of the required model parameters. Thermal imagery was acquired at intervals over a season of growth and ET estimated for *Cannabis sativa* L. in the KwaZulu-Natal Midlands, South Africa, and compared to ET_{EC} estimates obtained from field trials in the same location over the same period.

3.3 Method

3.3.1 Study site

The study took place in KwaZulu-Natal at a commercial farm, located approximately 20 km from Pietermaritzburg (29°31’37.0” S, 30°28’03.2” E). Approximately 7 ha was planted to hemp. Crop management was undertaken by the local farming business including weeding, irrigation, and fertigation. Security of the research site was ensured using an electric fence surrounding the field, with an overnight guard present. A short grass and weed cover was established in the tramline and regularly mown to reduce competition. The trial site was divided into three fields (North, East and South), each approximately 2.5 ha in size. The North and East fields contained hemp clones, while the South field contained feminized hemp seedlings.

Seedlings and clones were germinated in a greenhouse before being transplanted. Seedlings were transplanted into the South field on 21 November 2022, while clones were transplanted into the East field on 22 November 2022 and into the North field on 28 November 2022. Irrigation took place using dripper irrigation lines with a dripper applied 0.05 m away from each plant stem to avoid stem rot, with fertigation being applied through these dripper irrigation lines. Plants within rows were spaced 2 m apart, with an inter-row spacing of 2.5 m. Every fifth row was left fallow as a tram line to allow tractors to move through when spraying. The plants in the South field were ‘topped’, and their apex removed, to slow their vertical growth and encourage branching of the plants. This management strategy encourages a higher concentration of flowers to form before being harvested.

The underlying soil texture information was obtained using the Soil and Terrain (SOTER) database for South Africa, an international database of information on soil and terrain properties. The South African database was downloaded and imported into QGIS (version 3.28.11), where the soil category for the local farming business was determined. This soil category contained codes for its associated landform, lithology, and soil texture that were matched according to Batjes (2004) and Dijkshoorn, van Engelen and Huting (2008). The research site fell on soils that were well drained, with approximately 74% sand, 5% silt and 21% clay within the top 0.2 m of the soil profile and can be considered a sandy clay loam.

3.3.2 Image acquisition and data processing

A UAV (DJI Matrice 300; Plate 3.1) was flown over the research site every two weeks in the beginning of the season (when weather and logistics allowed) starting one month after planting, followed by every four weeks during the second half of the season, with a multispectral camera (MicaSense Altum, Seattle, USA) attached. A total of five flights were performed at an altitude of 100 m (Table 3.1). The irregularity of time between flights during the first half of the season, and the irregularity of time of day, was due to weather conditions and availability of the UAV and pilot.

Table 3.1: Date and time of UAV flights occurring over the growing season

Date	Time of flight
27 December 2022	11:05
18 January 2023	09:20
24 January 2023	11:07
23 February 2023	11:48
31 March 2023	09:38

Plate 3.1: DJI Matrice 300 series drone with mounted MicaSense Altum camera, used for imagery acquisition over the growing season

Raw images of each flight were imported into PIX4DFields to form an orthographic photo of the research site with a resolution of 0.07 m pixel^{-1}. After the orthomosaic image was clipped to the boundaries of the hemp field, the thermal index and NDVI layers were obtained from the orthophoto, after which the thermal layer imported into QWaterModel (version 1.5), a plugin within the QGIS platform (version 3.28). Both NDVI and ET_{QW} maps had a resolution of 0.07 m pixel^{-1}. The model was run for each flight with defined parameters for short wave irradiance (W m^{-2}), net radiation (W m^{-2}), ground heat flux (percentage of net radiation) and ambient air temperature (Kelvin); these parameters were acquired from the eddy covariance system on the ground within the trial site over the same period. Default atmospheric transmissivity, atmospheric emissivity and surface emissivity (0.7, 0.8 and 1.0, respectively) were used as defined by Timmermans *et al.* (2015), and as recommended by Ellsaßer *et al*. (2020). The minimum and maximum temperature parameters were calculated automatically by the model, with the highest temperatures corresponding to the hottest pixels in the image. To avoid the influence of extreme outliers, such as open water, the minimum temperature was defined as the value above the 0.5% lowest temperature in the image. After QWaterModel was run, the latent heat flux and evaporative fraction outputs for each flight were acquired from the model and multiplied together to calculate hourly ET_{QW}. Since the EF is assumed to remain constant during the day (Hoedjes *et al*. 2008), the upscaling of hourly ET_{QW} to daily ET_{QW} is performed through the multiplication of hourly ET_{QW} by the number of hours of evaporation per day (twelve hours).

3.4 Results

The QWaterModel (Figure 3.1 and Table 3.2) overestimated accumulated ET_{QW} from the hemp crop for the five days when images were captured. It predicted an accumulated ET_{QW} of 24.2 mm, while the EC system measured a total ET_{EC} of 16.9 mm over the same days. At a daily level, this overestimation took place in four out of five measurement days. The final flight of the season had the most comparable results to the EC system and recorded lower ET_{QW} than the EC system. QWaterModel estimated a daily ET of 7.7 mm on growing day 30 (27 December 2022), while the EC system measured 3.88 mm daily ET_{EC} on the same day. On day 124 (31 March 2023), QWaterModel underestimated ET, measuring 1.08 mm, while the eddy covariance system measured a total ET of 2.18 mm for the same day. The model performed optimally when ET was 1-2 mm and overestimated when ET was higher.

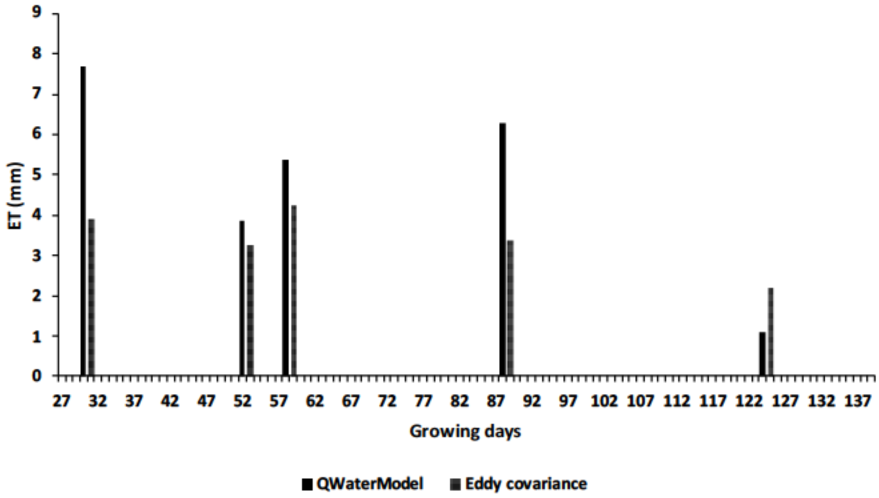


Figure 3.1: Modelled evapotranspiration using the QWaterModel against measured evapotranspiration using an eddy covariance system between December 2022 and April 2023

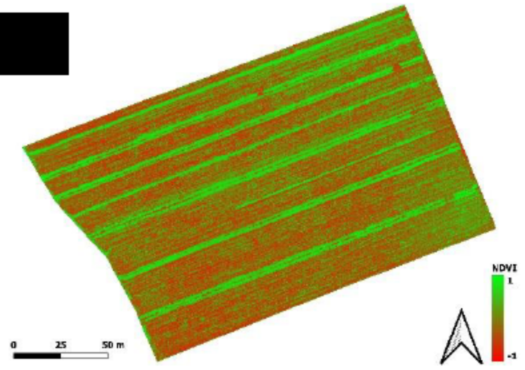
Table 3.2: ET comparison between QWaterModel ET (ET_{QW}) and ground-based eddy covariance measurements.

Date	ET_{QW} (mm)	EC (mm)
27 December 2022	7.70	3.88
18 January 2023	3.87	3.27
24 January 2023	5.37	4.24
23 February 2023	6.27	3.36
31 March 2023	1.08	2.18

Using a PIX4DFields Digital Elevation Model (DEM), the average height of the study site ranged from approximately 856 m above sea level on the western side of the field to 864 m above sea level on the eastern side of the field. As a result, ET_{QW} was higher on the western side of the field (Figure 3.2). ET_{QW} had high spatial variation, being influenced by surrounding weeds, grasses and bare soil. The Normalised Difference Vegetation Index (NDVI) was compared to ET_{QW} for each flight, occurring on 27 December 2022 (Figure 3.2 a), 18 January 2023 (Figure 3.2 b), 24 January 2023 (Figure 3.2 c), 23 February 2023 (Figure 3.2 d), and 31 March 2023 (Figure 3.2 e). Areas with high NDVI (hemp plants and weeds) were observed to have a higher ET_{QW}, while low NDVI values (bare soil) had low ET_{QW}. This is most easily distinguished between rows, where increased canopy cover from the surrounding short grass surface likely led to increased transpiration. This can be observed in Figure 3.2 d, just before harvest, where the hemp plants were the largest, and gaps (bare soil) between hemp plants were more defined. Areas of bare soil and low ET_{QW} are clearly visible in Figure 3.2 a, just after planting. The soil surface in Figure 3.2 a has a low NDVI of approximately zero (brown) whereas the weeded tramlines have an NDVI of close to one (green). The brown NDVI correspond with the red ET_{QW} and green NDVI with blue ET_{QW}. The high resolution of 0.07 m $pixel^{-1}$ makes it possible to zoom in and identify the NDVI and ET_{QW} of individual plants. Figure 3.2 b and d were both clipped due to a PIX4DFields processing error. These flights were reprocessed multiple times but could not be rectified. Approximately 1.3% of Figure 3.2 b and 0.4% of Figure 3.2 d is missing and therefore the effect on ET_{QW} estimates was considered negligible.

In the present study, a strong correlation between ET_{QW} and ET_{EC} was observed, with a good Pearson coefficient (r = 0.8) and coefficient of determination (R^2 = 0.67), indicating a strong linear relationship between the two variables. A further correlation between NDVI and ET_{QW} was performed for flights occurring on 23 February 2023 and 31 March 2023, where the hemp plants could be clearly distinguished from surrounding vegetation. QGIS was used to randomly select one hundred points across the field, each centred on a hemp plant, to extract their corresponding NDVI and ET_{QW} point values. A weak correlation (r = 0.015; R^2 = 0.0002) was returned for the flight on 23 February 2023, with the following flight (31 March 2023) returning a similar correlation (r = 0.2; R^2 = 0.04). This indicates NDVI is not a driver for ET_{QW}; rather, parameters such as net solar radiation, vapour pressure deficit, wind speed and relative humidity play a more significant role as drivers for ET (Ren *et al.* 2024).

[redacted]



27 December 2022; 11:05 am

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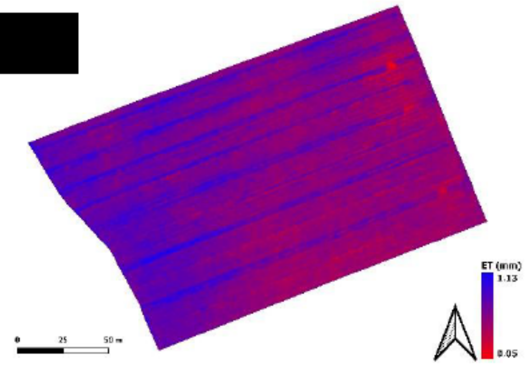

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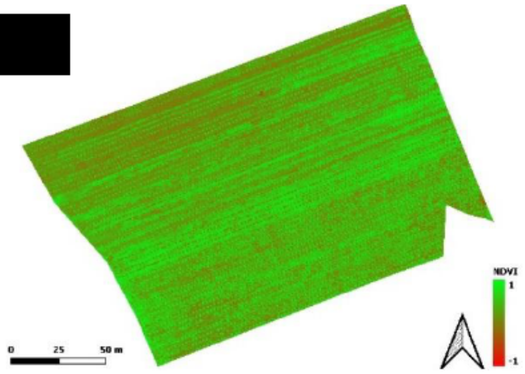

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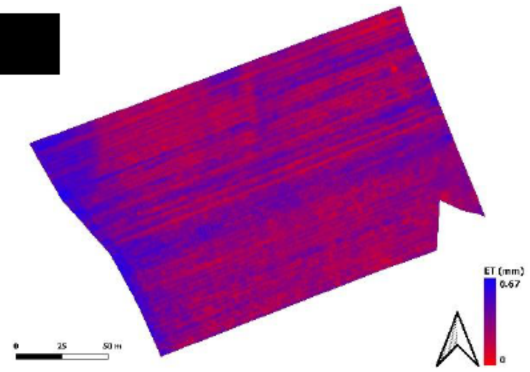

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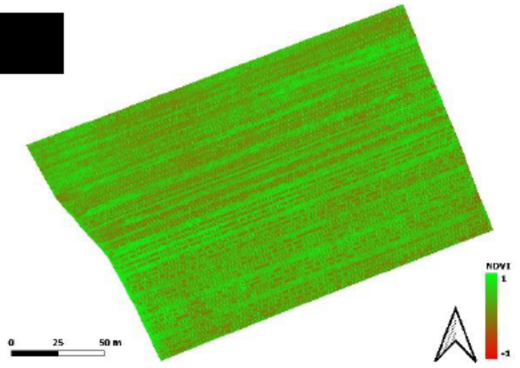

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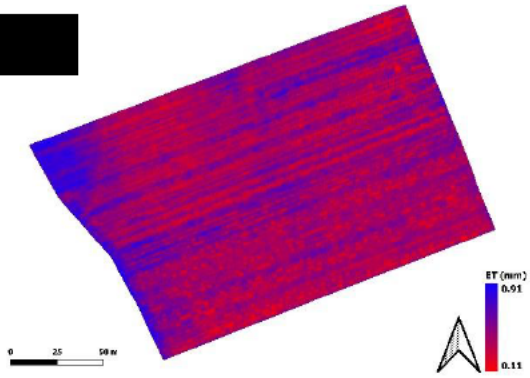

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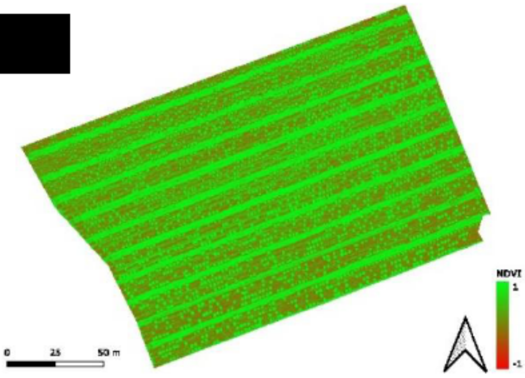

23 February 2023; 11:48 am

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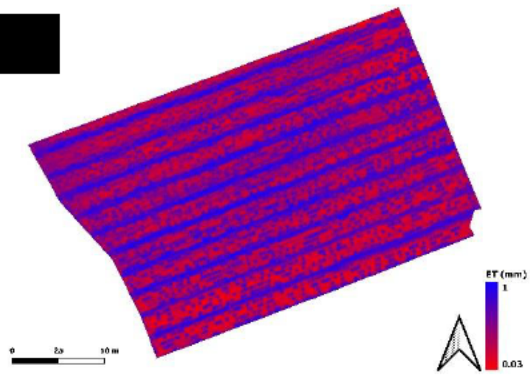
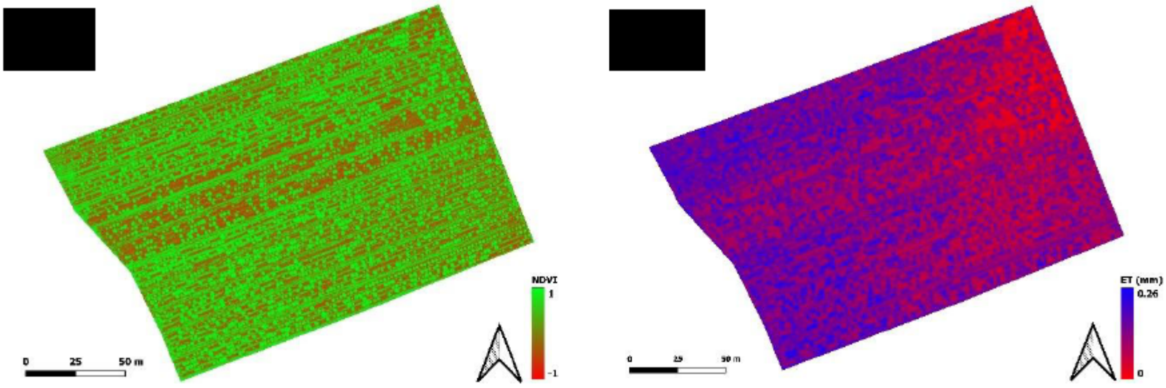


23 February 2023; 11:48 am



31 March 2023; 09:38 am   31 March 2023; 09:38 am

Figure 3.2: Comparison of (i) NDVI to (ii) QWaterModel ET throughout the growing season

3.5 Discussion

With the use of drone imagery and the QWaterModel it was possible to note the variation of ET_{QW} across the field and with individual plants. These images further illustrate how much water is used by grasses and weeds in the tram lines, by showing the contrast between weeded and vegetated areas. This provides an advantage in the understanding of the water-use of hemp. QWaterModel overestimated ET_{QW} at the beginning of the season (growing day 30), obtaining results of 7.7 mm day^{-1} as compared to 3.88 mm day^{-1} from the eddy covariance system (Figure 3.1). This could be due to the hemp plants being small, where ET_{QW} estimates would not fully represent the hemp plants and be influenced by the surrounding soil surface and weeds (Irmak, 2008). A lack of canopy cover, due to small plants, exposes the base soil beneath, affecting the reflective spectral characteristics of the crop (Kremneva *et al*. 2023). The model was observed to best perform when ET was low, between 1-2 mm (growing days 124 and 151). This concurs with a statement by the model authors, Ellsaßer *et al*. (2020), that the model performs best when ET_{QW} estimates are low, resulting in the strongest correlation between model predictions and eddy covariance measurements.

QWaterModel lacks post-processing options, and the colour scale of the output maps could not be adjusted or standardised after the model was run. The maximum ET_{QW} for each flight is represented by the same maximum colour on the map legend, regardless of the actual ET_{QW} value. This hampers the visual comparison of maximum ET_{QW} between flights as they all appear to have the same maximum values. For example, Figure 3.2 a (ii), c (ii), and d (ii) do not have a minimum ET_{QW} value of zero as all areas of the field were evaporating at the time of flight. The minimum value of ET_{QW} cannot therefore be set to zero, as the lack of post-processing options prevents the adjustment of colour scales of the output maps to accommodate these minimum values.

Although the model can be run with minimal parameters (requiring only the thermal image and time of day), the model developers stated that the more input parameters used in the model, the better the performance of the model. Ellsaßer *et al*. (2020) further observed that thermal images taken around noon result in higher estimates than eddy covariance measurements. In the present study, flights took place at 11 am on growing days 30, 58 and 88, while on days 52 and 124 flights took place at 9 am (Figure 3.1). However, on day 124, the underestimation of ET_{QW} takes place, with an estimation of 1 mm, while the EC system measured 2.18 mm ET. The authors of the DATTUTDUT model, the original model from which QWaterModel is based, stated that the DATTUTDUT model does not perform well when used under partial canopy cover (Timmermans *et al.* 2015). In this study the plant density was low, with the plants being spaced every 2 m, preventing full canopy closure. Male plants had to be removed from the trial site to prevent cross-pollination occurring, further adding to gaps in the canopy. The occurrence of male plants and ensuing gaps in the canopy was therefore unintentional.

Bulusu *et al*. (2023) utilised the DATTUTDUT model in a tropical rainforest in Sumatra, Indonesia, by applying the QWaterModel, which is the DATTUTDUT model with a graphical user interface. The DATTUTDUT model performed well when validated against eddy covariance measurements over grasslands in Germany (Brenner *et al.* 2018) and vineyards in USA (Xia *et al*. 2016). It performed well across two studies in tropical oil palm plantations in Sumatra, Indonesia (Ellsäßer *et al*. 2020, 2021). However, this conflicts with Nisa *et al*. (2021), who observed that the model had a low congruency to ground-based EC measurements across a field containing maize and fennel in southern Italy. Furthermore, in a comparison between the DATTUTDUT model and the TSEB model by Xia *et al*. (2016), the DATTUTDUT model was found to underperform since it does not consider row and inter-row sources of temperature contributions as it is a single-source model. The study stated that the evaporative fraction output had a wider range than that of the TSEB model, translating to discrepancies in latent energy measurements and hence ET_{QW} estimation. The DATTUTDUT model calculates the EF using net radiation minus soil heat flux to estimate turbulent heat fluxes. Therefore, the accuracy of net radiation and soil heat flux estimates influence the model outputs of the turbulent heat fluxes (Timmermans *et al*. 2015). However, provided the errors of both quantities are of the same magnitude, the effect on the available energy is comparatively low. In the present study, net radiation and soil heat flux values for the parameterisation of QWaterModel were obtained from the eddy covariance system present during the trial. The eddy covariance system had an energy balance closure of 87%, indicating that net radiation and soil heat flux measurements were accurate (Foken *et al*. 2010), ensuring the reliability of the EF. The need for net radiation and soil heat flux is a significant disadvantage of the model as these require expensive equipment and are not commonly measured, although can be estimated.

Xia *et al*. (2016) observed that the DATTUTDUT model was insensitive to errors in land surface temperature, unlike dual-source models. Furthermore, the study found that the area and spatial resolution of Land Surface Temperature (LST) maps, which is the orthomosaic used to generate ET_{QW}, significantly influences the DATTUTDUT model results. Brenner *et al*. (2018) compared the effects of spatial resolution on the results of the DATTUTDUT and TSEB model. They observed that the latent heat flux estimates vary with changes in the spatial resolution and show a tendency towards higher latent heat fluxes with higher spatial resolution. Overall, the sensitivity analysis of the model performance to image resolution showed that higher resolution leads to better EF estimates. Brenner *et al*. (2018) observed that at resolutions higher than 1 m pixel^{-1}, changes to image resolution have little to no impact on flux estimates, yet the higher the resolution, the greater the chance for the simultaneous presence of the minimum and maximum temperatures (wet and dry limits) that are essential for model calibration. In the present study, the QWatermodel's imported LST maps and output NDVI and ET maps were created at a resolution of 0.07 m pixel^{-1}, therefore, flux estimates were not affected as described by Brenner *et al*. (2018). Zipper and Loheide (2014) argued that the heterogeneity of a landscape complicates the definition of wet and dry limits and hinders the applicability of these models when the surface is neither totally bare, nor fully covered, by closed canopies. Model flux measurements, in general, are more in agreement with EC measurements when incorporated over a wide range of environmental conditions and over homogenous landscapes (Timmermans *et al*. 2007). However, gaps in the canopy occurred in the present study, due to the removal of male plants, resulting in a heterogeneous canopy structure. As the QWaterModel defined these wet and dry limits as a percentage of maximum and minimum temperature obtained from the LST map, rather than physical temperature values obtained from the eddy covariance system, the presence of this heterogeneous surface affected the model's ability to accurately determine these hydrological limits.

A topographical effect on the spatial variation of ET_{QW} over the study site was observed in the QWaterModel results. According to the DEM, the western part of the field is approximately 8 m lower than the eastern part, and the QWaterModel (Figure 3.2) modelled higher ET_{QW} flux and NDVI over the western part of the field than the eastern part. There are various plausible reasons for this, including soil depth, water availability, and wind exposure. As the hemp crop grew, the spatial variation of ET_{QW} became more pronounced. Such changes and variations are not evident from the EC system results, which is a point measurement and does not provide spatial information. The NDVI values of the crop helped explain ET_{QW} results as they reflect the volume of photosynthetically active vegetation and is often used as an indicator of the ecological state of landscapes (Phillips *et al*. 2008), and is one of the most common indices.

In the beginning of the season, hemp plants could not be individually identified using their NDVI values (Figure 3.2 a (i)), as they were to small, and as such there was no clear definition of ET_{QW} from the hemp plants themselves (Figure 3.2 a (ii)). Most of the ET_{QW} at this point occurred from the surrounding weeds and soil surface, with the soil being hotter than the canopy (Chirouze *et al*. 2014). The NDVI of every fifth row was higher as these rows were left empty and were used as tram lines for tractors. They therefore had a high presence of weeds or a short grass cover, resulting in higher ET_{QW} of these row spaces. These rows can be removed from the calculation of NDVI and ET_{QW} but would require the QWaterModel to be run 11 times for each flight, one for every four isolated rows of plants, adding up to 66 model runs in total. This is only practical if it can be automated in future. The effect of weeding and grass cover on ET_{QW} variability was effectively represented by Figure 3.2 c (i) and Plate 3.2 (both taken on the same day), where weeding of the inter-rows and around plants had taken place and a short grass surface had been established in the tram lines, now covering the bare soil (Plate 3.2). This resulted in a more uniform spatial pattern of ET_{QW} throughout the field (Figure 3.2 c (ii)). By the end of March, however, the NDVI of each hemp plant could be observed (Figure 3.2 e (i)), indicating high plant growth and vigour, while the corresponding ET_{QW} from the hemp plants can be seen as isolated points (Figure 3.2 e (ii)). The lack of canopy closure can be observed in Figure 3.2 d (i) and e (i), where there is a contrast between the NDVI of each plant and that of surrounding bare soil or weed surfaces.

Plate 3.2: The South field (24 January 2023) after weeding between the plants. A grass and weed cover was established in the tramline and mown to reduce competition. The research tower can be seen in the background

3.6 Conclusions

The QWaterModel is based upon the DATTUTDUT model and a number of the coefficients and parameters required for its effective operation originate from the latter model, effectively making QWaterModel a user-friendly interface for the implementation of the DATTUTDUT model. QWaterModel was applied to estimate the ET of a hemp crop over a full growing season in the KwaZulu-Natal Midlands, South Africa. These results were compared to ET results obtained using eddy covariance techniques in the same location over the same period.

The UAV provided flexibility in comparison to satellite imagery as it could be flown when needed. However, weather conditions and UAV availability were a limitation over the study period. Over the five UAV flights that took place throughout the growing season, QWaterModel was found to overestimate ET_{QW} of hemp on four occasions. On the last flight QWaterModel underestimated ET_{QW}. However, a good correlation was found between ET_{QW} and ET_{EC}. NDVI had a low correlation with ET_{QW} and was therefore not a driver for ET_{QW}. However, NDVI and ET_{QW} spatial results were similar, showing that NDVI can rather serve as an indicator of ET_{QW}, with high NDVI corresponding with high ET_{QW}. The NDVI and ET_{QW} showed a similar trend over the season, reflecting the changes in crop size, weeding and tramline grass-cover. The ET maps indicate the variability of ET_{QW} across the field from west to east and captured the differences between weeded, unweeded and healthy hemp plants. This successfully highlights the differences in water use between the crop rows, inter-rows, and tramlines, and growers can potentially make significant water savings by management of the groundcover between these rows which is particularly significant in water-stressed catchments.

A low planting density and removal of male plants caused a lack of canopy closure, affecting the accurate estimation of ET_{QW}, as a heterogeneous landscape generates inconsistent model outputs when using single-source models, such as QWaterModel. This is seen by the overestimation of ET_{QW} in the beginning of the growing season. This underscores that while QWaterModel successfully demonstrated its applicability in spatial ET estimation, future research could utilise a dual-source model such as the Two-Source Energy Balance (TSEB) model, that would likely have offered better ET estimation by separately accounting for the contributions of the plant and soil surfaces. The occurrence of male plants in the trial was unintentional and hindered the accurate estimation of ET_{QW}. Had it been known beforehand that male plants would occur, the selection of a model for this study would have been reconsidered. The findings of this study highlight QWaterModel's effectiveness in assessing the spatial variability of ET_{QW} as a user-friendly tool, however, it highlights the importance of model selection based on plant phenology, and other influencing factors, such as presence of weeds.

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CHAPTER FOUR

SYNTHESIS

4.1 Introduction

Currently the agricultural sector accounts for approximately 66% of South Africa's water usage (DWS, 2021). With the effects of climate change on an already water-stressed country, the demands on the limited water availability are ever-increasing. This invites the need for research into the cultivation of water-intensive crops such as hemp, such as its evapotranspiration (ET), potential impacts on water resources and downstream water availability. The South African National Water Act (No. 36 of 1998) mandates the regulation of land-based activities that reduce streamflow by declaring them to be Streamflow Reduction Activities (SFRA). This study provided water-use data to determine if hemp is a potential SFRA by assessing the ET of hemp over a season of growth in the KwaZulu-Natal Midlands, South Africa. However, it does not seek to answer the question on SFRA, as the actual determination of a SFRA requires extensive modelling of the effects of cultivation on downstream water availability and ecosystem sustainability (Dye & Versfeld, 2007), and is beyond the scope of this study.

There is a paucity of information on the water requirements of open-field cultivation of hemp (Bauer *et al*. 2015; Pejic *et al*. 2018). The research presented here adds new knowledge and aids in the understanding of the hydrological dynamics of hemp, its potential impacts on water resources, and downstream water availability. The results support the development of regulations surrounding its cultivation and helps to inform public opinion. The calculation of a crop coefficient for hemp is invaluable for hydrological calculations in global climatic biomes and assists in modelling applications of hemp, such as in streamflow reduction modelling.

The utilization of remote sensing techniques allows the assessment of ET variability across a field, that cannot be seen from ground level. The QWaterModel (Ellsaßer *et al.* 2020) was used as a graphical user interface for the implementation of the DATTUTDUT (Deriving Atmosphere Turbulent Transport Useful To Dummies Using Temperature) model (Timmermans *et al*. 2015), and has performed well in international literature. QWaterModel obtained a strong correlation to ground-based eddy covariance measurements in the present study and clearly showed the spatial relationship between the Normalized Difference

Vegetation Index (NDVI) and ET. The visual ET variability helps growers understand the hydrological dynamics of their field and aids in the management of water in water-scarce areas.

4.2 Limitations

Permits for the cultivation of the crop are required to legally cultivate hemp. Finding a suitable research site was challenging but fortunately a nearby business with a license to grow hemp provided a suitable research site in terms of area planted, security, crop variety, irrigation, and access.

The EC technique is the international standard in ET measurement but is a point measurement and has a measurement footprint that shifts depending on factors such as measurement height above the crop, wind speed and wind direction. Fortunately, the field trial site was extensive and relatively flat, providing a suitable location for EC measurements and the results are representative of the hemp ET.

The potential threats to achieving accurate datasets were primarily from: birds landing on the equipment and leaving mud on sensors, power failure, computational errors, storms, and theft. The research tower and sensors were damaged during a large storm. The storm caused extensive damage to the hemp crop, with lodging and breaking of branches. Fortunately, the hemp plants recovered quickly.

The total area planted to hemp was divided into three fields (North, East, South). Each field had a different planting date, making the accurate measurement of ET of hemp difficult as it alters throughout the plant's growth cycle. This made it imperative to understand wind direction to determine which plants would influence the latent heat fluxes. The removal of male hemp plants affected ET results by reducing the number of transpiring plants. This hampered efforts to measure LAI as some of the plants used for continual LAI measurement were removed, possibly affecting results. Hemp is not traditionally cultivated in South Africa, and the agronomic practices surrounding its cultivation, such as planting density, male plant removal and seedlings versus clones, are still under development.

4.3 Future research opportunities

- Although this study provides data of the crop coefficient, ET and WP of hemp, additional hydrological modelling is required to ascertain the impact of cultivation on downstream water availability and ecosystem sustainability (Dye & Versfeld, 2007).
- The South African regulatory framework is constantly evolving, with South Africa undergoing rapid cannabis policy change (Institute for Economic Justice, 2023). This is being coordinated through the National Cannabis Masterplan (NCMP). There are high expectations for the future of the South African cannabis industry, with significant potential for job opportunities, industrial development, and revenue generation, which will necessitate further research into plant phenological, environmental, industrial, and economic aspects.
- Previous studies focusing on the outdoor cultivation and production of hemp have concentrated on fibre (Cosentino *et al*. 2013; Tang *et al*. 2016, 2022), stem (Tang *et al*. 2017), and seed (Tang *et al*. 2016, 2017), with the present study focusing on bud production. There are thus many aspects to be studied regarding outdoor hemp productivity.
- The use of QWaterModel was successful in understanding the variability of ET across the field, demonstrating the effect of weeding and elevation on ET, however a more comprehensive model is recommended in the estimation of ET. This is because QWaterModel is a single-sourced model, assuming total canopy cover and thus a homogenous surface, which was not the case in this study. The gaps in the canopy occurred due to the removal of male plants, preventing a homogeneous canopy. Had this been known beforehand that male plants would be present, the selection of a model for this study would have been reconsidered.
- Weeds and grasses have a high water use at times and management of the surface where there is no canopy closure of the hemp plant is potentially important in water scarce areas.

4.4 Conclusions

The aim of the study was to calculate the ET and WP of hemp over a season of growth in the KwaZulu-Natal Midlands, South Africa. This study provided water use and crop modelling data to support the evaluation of hemp as a potential SFRA.

The objectives of the research were to:

- quantify the ET losses and crop coefficient for a hemp crop over a growing season;
- determine the water productivity of hemp; and
- assess a remote sensing technique to understand ET variability across a cultivated field.

This study provides the first water-use and productivity measurements of hemp grown in South Africa. The evapotranspiration of hemp was higher than comparative studies, with a lower water productivity being found than other results reported. However, the crop coefficient is lower than other crops, indicating that the lower water productivity found in this study could be attributed to the difference in agronomic and cultivation practices, such as planting density. Although evapotranspiration is site specific and cannot be extrapolated, the crop coefficient provides a standardized reference for crop water use. However, adjustments will need to be made based on local climate and management practices. The crop coefficient agrees with international studies and provides a benchmark for modelling the water-use of hemp across diverse climatic areas.

The QWaterModel was considered to implement the DATTUTDUT model with a graphical user interface. The ET of QWaterModel (ET_{QW}) was compared to measurements collected from an eddy covariance system within the trial site. QWaterModel predictions correlated well with EC measurements, and it was found that QWaterModel overestimated total ET_{QW} in four out of five measurements, with inaccuracies being attributed to the heterogeneity of land surface cover and model simplicity. Predicted ET_{QW} in the beginning of the season represented mainly soil and weed ET, due to small plant size. The spatial variability of ET was similar to NDVI over the cultivation area, with higher ET occurring on the western part of the field associated with an elevation difference.

A framework for remote sensing modelling is provided for UAV thermal imagery and reveals the variability of UAV-derived NDVI and ET indices across a field that cannot be easily measured using ground-based techniques. Furthermore, the study underscores the importance of management of inter-row areas and tramlines, allowing growers to make informed decisions about water management in water-scarce areas.

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