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THE HYDROLOGICAL BALANCE: CROP EVAPOTRANSPIRATION AND WATER USE EFFICIENCY: THE ART OF REVIEW

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Abstract

This research delves into the pivotal importance of evapotranspiration (ET) in refining water management strategies for agriculture, especially in the context of escalating global climate change and increasing water scarcity. It highlights the necessity of precise ET measurement and modeling, which face considerable challenges stemming from the diversity of irrigation methodologies, crop types, and management practices that render conventional tabular ET methods insufficient. By synthesizing findings from various studies, the paper presents innovative approaches that successfully estimate ET across diverse spatial and temporal scales. Key investigations focus on maize water usage and productivity in the semiarid Southwest United States, employing locally adapted crop coefficients in conjunction with FAO guidelines. Results demonstrate marked variability in actual evapotranspiration (ETa) and associated irrigation requirements, carrying significant implications for regional water management frameworks. Furthermore, the review addresses breakthroughs in remote sensing technologies and advanced modeling techniques that improve ET estimation accuracy, particularly through the integration of satellite-derived data. The correlations between model outputs and empirical data emphasize the critical need for continuous improvement and validation of ET models. Emerging research trends indicate a growing reliance on information technology to enhance ET modeling resolutions and emphasize the necessity of understanding the complex interactions between irrigation practices and ET dynamics. This comprehensive overview of contemporary ET research illustrates its relevance to sustainable agricultural practices and offers actionable recommendations for future explorations that adapt to evolving environmental conditions. Ultimately, the insights garnered from this study provide a pathway for boosting irrigation efficiency and water productivity, thereby supporting the sustainability of agricultural practices globally amidst the challenges posed by climate change.

***Key Words*:** Evapotranspiration, Irrigation management, Remote sensing applications, Water use efficiency, Crop water requirements, Water scarcity, Agrometeorology, Lysimeters, Crop modeling, Water footprint.

1. INTRODUCTION

Efficient management of water resources has become increasingly vital, particularly in arid and semi-arid regions where agriculture heavily depends on irrigation. In these areas, water usage can exceed 70-80% of the total available water, indicating significant pressure on scarce resources (Fereres & Soriano, 2007). Irrigated agriculture currently produces over 40% of the world's food while occupying only about 17% of the land used for food production. However, this balance is threatened by rising populations and climate change. While some regions may experience increased rainfall, many water-scarce areas are expected to endure harsher drought conditions, leading to diminished river flows and higher evaporation rates. Consequently, competition for water resources is becoming more intense (Perry et al., 2008; IPCC, 2007).

Understanding evapotranspiration (ET)—the process of water moving from the land into the atmosphere—is crucial for optimizing water use in agriculture. Accurate estimation of ET is essential not just for efficient crop management and irrigation practices, but also for wider assessments of ecological health and the economic implications of climate change. Traditional methods of estimating ET, such as those found in the FAO-56 guidelines, have not kept pace with the rapid evolution of agricultural practices that now include a wide variety of crops and advanced growing techniques like greenhouse cultivation.

In regions like the Southwestern United States, water management challenges are exacerbated by prolonged droughts and increasing evaporation demands. A staggering 92% of cropland in this area is irrigated, revealing a reliance on water-heavy agricultural practices. As climate change continues to unfold, worries about the sustainability of these practices intensify, especially with the concerning figure that irrigated agriculture accounts for about 50% of total water use in California—an already stressed water environment.

This paper aims to review the importance of ET in agricultural water management, focusing on methods for accurately estimating crop ET, particularly in places where traditional methods may struggle. The study will explore ways to enhance water use efficiency, such as deficit irrigation and partial root-zone irrigation, alongside innovative techniques like remote sensing technologies. By improving the accuracy of ET measurements and promoting effective strategies for sustainable irrigation, this review seeks to tackle the ongoing issues of water scarcity and climate change in contemporary agriculture. Ultimately, understanding and accurately estimating ET will pave the way for effective water management strategies, contributing to the sustainability of agricultural systems vital for satisfying future food needs.

2. Crop evapotranspiration – (Concepts)

Crop evapotranspiration is a critical process that involves the combined loss of water from the soil and plants to the atmosphere through two main mechanisms: evaporation and transpiration. The term "evapotranspiration" was first introduced by Thornthwaite in 1948 to emphasize the intertwined nature of these processes, which are often challenging to separate. Evapotranspiration is driven by energy from the sun and influenced by the movement of water vapor from the Earth's surface into the atmosphere (Tucci and Beltrame, 2009). This transfer of water occurs via molecular and turbulent diffusion. Understanding Evaporation and Transpiration

Evaporation refers to the conversion of liquid water into vapor and occurs on various surfaces, including lakes, rivers, pavements, soils, and vegetation. On the other hand, transpiration is the process, where water exits plants and enters the atmosphere, primarily through tiny openings known as stomata. This stomatal movement accounts for over 90% of the water loss from plants.

Measuring evapotranspiration can be accomplished using several techniques, including lysimeters, eddy covariance, the Bowen ratio method, water balance equations, sap flow measurements, and satellite remote sensing. Among these, the Bowen Ratio Energy Balance (BREB) method is particularly popular due to its simplicity and reliability. Recent advancements in sensor technology have also made the Eddy Covariance method more prevalent.

2.1 Crop Coefficient (Kc)

The crop coefficient (Kc) is a key metric in estimating crop evapotranspiration, representing the ratio of actual crop evapotranspiration to reference evapotranspiration. First introduced by Jensen in 1968 and elaborated in FAO Bulletin 56 by Allen et al. (1998), this method offers the advantage of requiring only daily weather data for estimating reference evapotranspiration. This reference value is then multiplied by a dimensionless Kc that changes according to the growth stages of the crop. Specifically, crop evapotranspiration can be calculated with the formula:

$$ET = K_c.ET_0$$

where ET_0 (in mm/day) signifies reference evapotranspiration. According to Allen et al. (1998), various weather factors are integrated into the estimate of ET_0. Therefore, ET_0 serves as a measure of climate demand, and Kc primarily varies based on specific crop characteristics, only slightly influenced by climatic conditions.

FAO-56 provides Kc values for the initial, middle, and end stages of crop growth—designated as , K_{c-ini}, K_{c-mid} and K_{c-end}, for numerous crops. These Kc values are primarily calibrated for sub-humid climates, characterized by average daily minimum relative humidity (RHmin) of around 45% and moderate wind speeds averaging 2m s^{-1}. For different climate types, such as humid, arid, or semi-arid regions, it's suggested that modifications to these values are needed in accordance with the equations proposed in FAO-56 (Allen et al., 1998).

However, relying solely on these values can lead to crop evapotranspiration (ETc) estimates that may diverge significantly from actual measurements (Hunsaker et al., 2003). It has been shown that experimentally derived values for K_{c-ini}, K_{c-mid} and K_{c-end} often differ from those in FAO-56. For example, Farahani et al. (2008) conducted a comparison involving cotton evapotranspiration based on FAO-56 Kc and experimental Kc, revealing differences ranging from 10% to 33% over three years in Mediterranean environments. Consequently, to accurately apply this methodology, it's essential to obtain experimental data on Kc curve values that reflect local climatic and water management conditions. Allen et al. (1998) recommend gathering evapotranspiration data from long-term experimental observations to improve accuracy.

2.2 Bowen Ratio Energy Balance (BREB)

The BREB technique estimates crop evapotranspiration using latent heat flux density derived from the energy balance equation. Neglecting factors such as advection effects and energy stored in the canopy, the energy balance can be expressed as:

$$Rn = LE + H + G$$

where:

Rn = net radiation flux density LE= latent heat flux density

H = sensible heat flux density G = soil heat flux density

2.3 Eddy Covariance Method

The Eddy Covariance method is recognized as one of the most accurate methodologies for measuring and calculating turbulent fluxes within the atmospheric boundary layer. According to Burba and Anderson (2007), this technique enables direct flux measurements without relying on empirical constants, making it a robust approach for researchers. However, the implementation of the eddy covariance method is not without its challenges. It involves complex mathematical principles and requires careful setup and extensive data processing. This complexity poses significant obstacles, especially for non-experts who may struggle with the intricacies of system design and the management of large datasets, as noted by Arya (2001), Burba and Anderson (2007), and Stull (1998). The fundamental concept of eddy covariance is based on the statistical correlation (or covariance) between vertical fluxes of heat or vapor in the upward and downward trajectories of turbulent eddies (Allen et al., 2011). The method operates on the premise that all atmospheric constituents exhibit short-term fluctuations around their long-term average values, as discussed by (Oke, 1978). This phenomenon of turbulence is integral to the movement of eddies, which transport various properties derived from different regions within the atmosphere. Therefore the value of an entity variable in time (s) consists of its mean value ($\overline{s}$), and a fluctuating part (s'), (as illustrated in Fig.2.1).

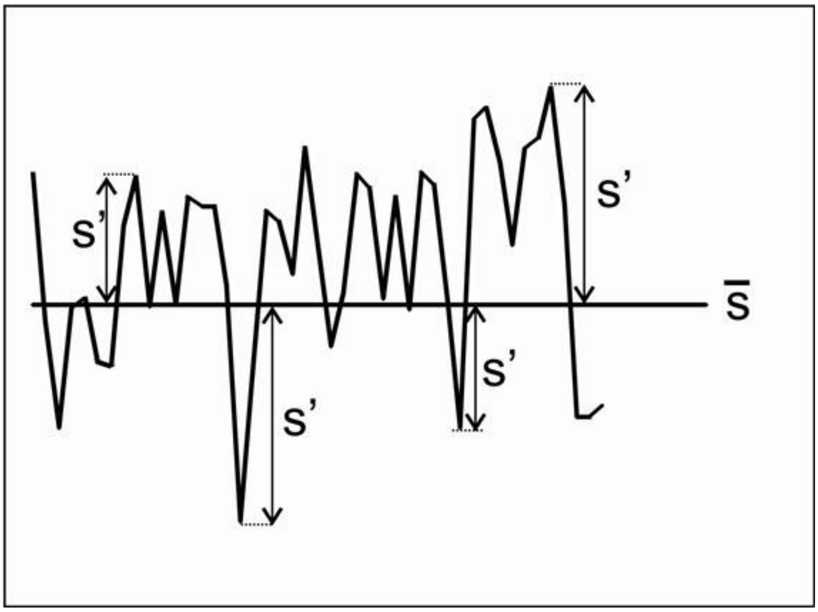

Fig.-2.1: Instantaneous values of turbulent variable is obtained by its mean ($\overline{s}$) and flutuing values (s') (Arya, 2001; Folken, 2008; Oke, 1978,)

Thus, its instantaneous value is obtained from following equation, also known as Reynold's decomposition $s, \overline{s}, s'$ where the overbar indicates a time-averaged property and the prime signifies instantaneous deviation from the mean.The air flow over an agricultural ecosystem can be understood as a horizontal flow of numerous rotating eddies, according to Fig. 2.2. Each eddy has three-dimensional components, including vertical movement of the air (Burba & Anderson, 2007).

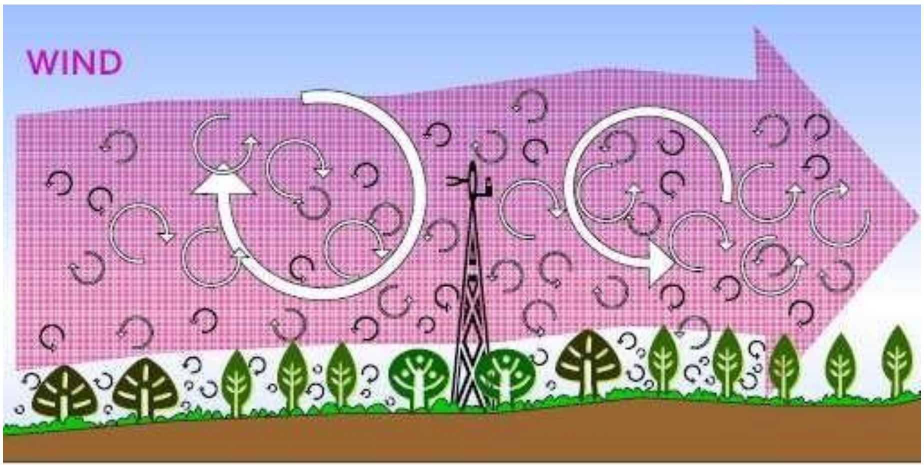

Fig.-2.2: Air flow over an agricultural ecossystem (Source: Burba & Anderson, 2007)

3. Water use efficiency

The burgeoning human population has precipitated an escalating demand for food. Concurrently, in arid and semi-arid regions, the scarcity of potable water has rendered the efficient use of this essential resource increasingly imperative. As highlighted by Perry et al. (2009), competition for limited water resources is becoming visibly pronounced across diverse geographies from the Murray-Darling basin in Australia to the Middle Eastern rivers, from the southern African waterways to the aquifers in northern India, and even the Ogallala aquifer in the central United States. The predominant factor contributing to the shortage of drinkable water is the aggressive exploitation of natural resources, coupled with a stark lack of effective public policies for water resource management, particularly in developing nations. In instances where water utilization remains unregulated, the disparity between supply and demand manifests itself through declining water tables, drying estuaries, and deteriorating aquatic ecosystems (Perry et al., 2009). Consequently, enhancing water-use efficiency across all human activities be it domestic, industrial, or agricultural has become a necessity. Within this framework, optimizing water usage in irrigation takes on significant importance, as it accounts for nearly half of global food production. Agriculture is currently the foremost consumer of water worldwide, utilizing over 80% of the available water resources in arid and semi-arid regions. Furthermore, the dual challenge posed by a rising population and the effects of global climate change threatens the security of global food supplies (Strzepek & Boehlert, 2010). This predicament arises from the intensified demand for irrigated agriculture, which increasingly rivals the demands of other sectors, including domestic and industrial consumption. In regions where water availability is constrained, it is essential for farmers to prioritize maximizing net income per unit of water utilized rather than focusing solely on income per unit area (Fereres & Soriano, 2007). This shift in perspective reflects the pressing challenge within the irrigation sector: enhancing agricultural productivity while using less water (Kassam et al., 2007; Fereres & Soriano, 2007). The concept of water productivity (WP) emerges as a crucial metric, representing the relationship between the net economic benefits derived from agricultural activities—such as crop production, forestry, fishing, and livestock—and the water consumption involved in generating these benefits (Kassam et al., 2007; Molden, 1997; Steduto et al., 2007). More specifically, WP is quantified as the amount of crop yield produced (in kg ha^{-1}) per unit of water applied or consumed (in m^3 ha^{-1}) (Molden, 1997; Teixeira et al., 2009). Publications by various researchers recommend analyzing WP in terms of crop ET, as this measure encompasses both irrigation water and ancillary sources such as rainfall, capillary rise, and fluctuations in soil moisture levels (Droogers & Kite, 1999). Conversely, Oweis et al. (2011) assert that while WPET serves more as a biological indicator, WPI is influenced by the operational effectiveness of the irrigation system and various losses incurred beyond mere transpiration. Consequently, the imperative confronting the irrigation sector is to enhance productivity in conjunction with reduced water consumption, effectively encapsulated in the goal of increasing water productivity. Various strategies have been employed in irrigation management to boost WP, with Partial Root Zone Irrigation (PRI) and Deficit Irrigation (DI) being among the most prevalent. PRI is an innovative approach wherein only a portion of the root zone is irrigated through meticulous design and management, leaving the remainder of the root system to experience dryer conditions (Mavi & Tupper, 2004; Tang et al., 2010; Zhang et al., 2001). The cycle of irrigating the wet and dried segments is adjusted based on the soil's drying rate and the crops' water consumption (Kang & Zhang, 2004; Tang et al., 2010). Zhang et al. (2001) suggest this practice may help in minimizing water usage while sustaining biomass production through two theoretical principles. First, fully irrigated plants typically exhibit wide stomatal openings; minor constriction can dramatically reduce water loss with minimal effect on photosynthesis. Second, sections of the root system in dried soil can send signals to the shoots that influence stomatal regulation, effectively curtailing water loss. Nevertheless, the anticipated benefits may not always manifest in field conditions, as prolonged drought can lead to anatomical changes in the roots, underscoring the necessity of alternating irrigation between different segments of the root system (Kang & Zhang, 2004; Zhang et al., 2001).

Deficit Irrigation (DI) is another widely adopted strategy aimed at augmenting WP. DI entails the application of water below the full ET requirement, whereby irrigation is scheduled based on a predetermined fraction of the total water requirement (Morison et al., 2008). This approach is often referred to as Regulated Deficit Irrigation (RDI). According to Fereres & Soriano (2007), assessing the full water requirement is pivotal in quantifying DI. Experimental studies have demonstrated that DI contributes to enhanced WP (Zwart & Bastiaanssen, 2004), establishing itself as a vital strategy to maintain agricultural productivity in arid and semi-arid regions facing diminishing water resources. In addition to improved irrigation efficiency, DI offers potential cost savings and environmental benefits. As noted by Fereres & Soriano (2007), several factors contribute to the increased WP observed under DI conditions. One significant factor is the intricate relationship between crop yield and irrigation water amounts. Moderate irrigation can enhance crop ET linearly until a threshold is reached, beyond which the relationship becomes curvilinear, as excessive irrigation may not equate to increased ET and can result in losses. This threshold is referred to as IW (the point beyond which WP begins to decline) and IM (the point beyond which additional irrigation no longer increases yield) (Fereres & Soriano, 2007).

To investigate the effects of DI on water balance and yield in irrigated cotton crops in Brazil's semi-arid regions, simulations were performed using the SWAP model. This model was calibrated and validated based on data collected during two experimental campaigns in the state of Rio Grande do Norte, Northeast Brazil, following the calibration and validation procedures detailed by Bezerra (2011). The experimental sites utilized sandy-clay-loam soil, classified by the USDA. The SWAP model, which simulates the vertical transport of water, solutes, and heat in both saturated and unsaturated zones relative to crop growth, has undergone continuous development since its original formulation by Feddes et al. (1978); the version employed in this study is SWAP 3.2, as described by Kroes et al. (2008). As articulated by Droogers et al. (2010), the SWAP model necessitates various types of input data categorized as state variables, boundary conditions, and calibration/validation data. The primary state variables pertain to soil and crop characteristics, often described with van Genuchten-Mualem parameters, referred to as hydraulic functions. Crop growth and yield for cotton were simulated utilizing a detailed growth module based on the World Food Studies (WOFOST) model (Supit et al., 1994), which incorporates factors such as incoming photosynthetically active radiation absorbed by the crop canopy, leaf photosynthetic characteristics, and the mitigating effects of water and salt stress on crop yield (van Dam et al., 2008).

The relationship between crop growth and irrigation increase is prominently illustrated by the Leaf Area Index (LAI) depicted in Figure 3. Typically, as soil moisture levels rise, so too does the leaf area and, consequently, the LAI of cotton crops. A reduction in crop growth results in lower ground cover, which in turn exacerbates water loss through soil evaporation. This phenomenon is particularly pronounced when a sprinkler irrigation system is utilized frequently. Such systems can lead to intense surface wetting; however, inadequate crop coverage often leaves the soil exposed, thus facilitating inevitable evaporation losses (López-Urrea et al., 2009; Cavero et al., 2009).

Table 1 summarizes the mean values for irrigation (I), yield (Y), and evapotranspiration (ET) of cotton crops across all treatments simulated by the SWAP model. Notably, increases in irrigation depth correspond with elevated ET values. However, this does not necessarily imply a proportional increase in yield. This finding aligns with the observations made by Fereres and Soriano (2007), who noted that while crop yield tends to rise with irrigation advancements from deficit irrigation (DI) regimes to full irrigation conditions excessive irrigation can lead to diminished yields. In fact, in treatments with excessive irrigation depth, yields were observed to decline, falling below those of the DI_{75} treatment. This yield reduction under excessive irrigation conditions is attributed to an overabundance of vegetative growth, which can hinder ultimately productive outcomes

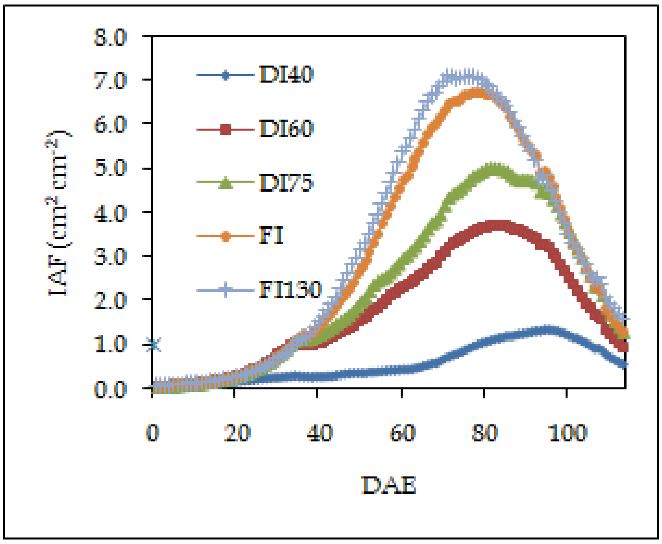

Fig.-3.1:. IAF curves of all treatments simulated by SWAP.

Table 1.-: Irrigation depth, yield and evapotranspiration of cotton for each treatment simulated by SWAP model

	I (mm)	Y (kg ha-1)	ET (mm)
DI_{40}	356	1367	345

DI_{60}	533	2167	491
DI_{75}	666	3336	625
FI	899	3517	734
FI130	1154	3317	761

The relationships between evapotranspiration and irrigation, as well as between yield and irrigation, are illustrated in Figure 3.2 (top). Additionally, Figure 3.2 (bottom) depicts the correlations between Water Productivity per unit of Evapotranspiration (WPET) and irrigation, alongside the relationship between Water Productivity per unit of Irrigation (WPI) and irrigation. The curves presented in these relationships elucidate the guidelines proposed by Fereres and Soriano (2007) regarding deficit irrigation practices. As indicated in Figure 4, the points denoted as IM (Irrigation Management) and IW (Irrigation Yield) are not situated within the same treatment category. Crop yield exhibited an increase from the DI40 treatment, reaching its peak at the full irrigation (FI) treatment. In contrast, the yield for the FI130 treatment declined relative to the FI treatment, aligning closely with the yield observed in the DI75 treatment. Notably, evapotranspiration (ET) increased across all treatments, corroborating the assertion by Fereres and Soriano (2007) that additional irrigation results in heightened crop ET values. This pattern was particularly evident from the transition between FI and FI130, wherein crop ET escalated while yield did not exhibit the same trend. It was in the FI treatment that the IM point was identified, whereas the IW point was located in the DI75 treatment, where performance indicators reached their optimum values.

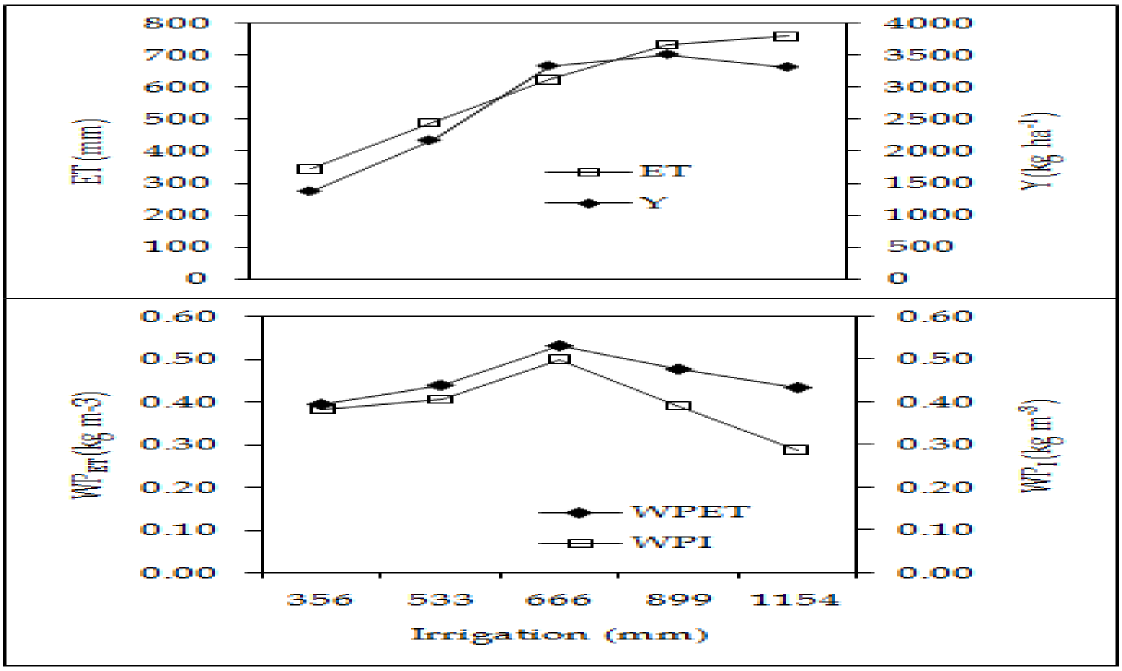

Figure.- 3.2: Relationships between ET and irrigation, as well as yield and irrigation (upper section), and the curves of WPET and WPI for cotton in Brazil's semi-arid regions (lower section). The average WPET ranged from 0.395 to 0.535 kg m^3 over the course of both years, as detailed in (Table 1). The DI_{75} treatment demonstrated the highest WPET, while DI_{40} exhibited the lowest values in both years. Interestingly, WPET values increased with escalating water stress; nevertheless, a decline in WPET was observed beyond FI, culminating in a scenario where the excessive irrigation treatment FI130 yielded WPET values equivalent to those of DI_{60}. It is noteworthy that WPI consistently remained lower than WPET, diverging from findings in previous studies (Dağdelen et al., 2009; Du et al., 2008; Ibragimov et al., 2007; Singh et al., 2010). This discrepancy can be attributed to the groundwater depth characteristic of the Brazilian semi-arid environment, which inhibits capillary rise. Consequently, the water uptake by plants is predominantly constrained to the irrigation water provided.

4. LITERATURE SURVEY

1. This literature survey examines the estimation of crop evapotranspiration (ET) in Udham Singh Nagar district, employing the modified Priestley-Taylor (MPT) model alongside Landsat imagery. The study identifies significant challenges in daily ET estimation, primarily related to the need for accurate data inputs and environmental influences such as cloud cover and land use changes. Utilizing Landsat 8 and 9 datasets from the 2022-23 period, the research estimates average ET values ranging from 1.33 to 3.20 mm/day from December to April, with validation metrics indicating strong model performance ($R^2 = 0.71$, RMSE = 0.62 mm/day). The MPT model is commended for its simplicity and effectiveness in areas lacking ground-based data, facilitating diverse crop assessments without heavy reliance on local meteorological measurements. The role of remote sensing is emphasized for enabling broader spatial analysis that extends beyond limited point measurements, revealing spatiotemporal variations in ET influenced by local climatic conditions. The review also discusses the integration of the Ts-VI triangle method within the MPT framework, enhancing adaptability across various cropping systems. However, limitations concerning the model's sensitivity to temperature variations in hilly terrains and the necessity for recalibration in different agroclimatic contexts are noted. Recommendations for future research include improving model calibration and applicability to a broader range of crops and environmental conditions, thereby highlighting the crucial role of remote sensing technology in advancing agricultural studies. Overall, the findings contribute

valuable insights into sustainable water management strategies in agricultural landscapes.

2. Opportunities for improvement Owing to the large share of rice, and particularly lowland rice in these cropping systems, increasing water productivity of rice would increase the water productivity of the whole basin. Mainuddin and Kirby (46) outlined the main opportunities for improvement. These include using high-yielding varieties, increasing application of fertilizer, herbicides and pesticides, and supplementary irrigation. Upland crops such as coffee, vegetables and peanuts outperform rice in terms of economic return per millimetre water use. Increasing the share of these high-value upland crops, Mainuddin and Kirby (46) conclude, can increase farm income and reduce poverty with unlikely trade-offs in terms of food security in the basin.

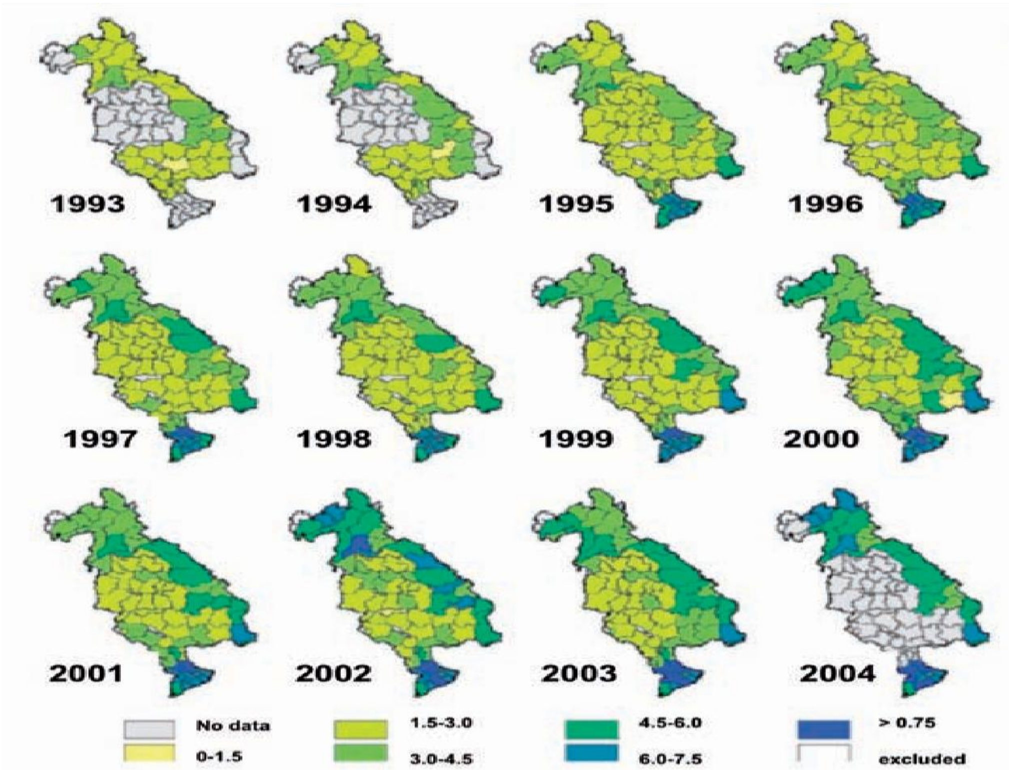

FIGURE 4.1: Mekong river basin yield per unit evapotranspiration of rice at a regional scale, in kg grain HA-1 MM-1

3. Evapotranspiration (ET) is crucial to the global water cycle, especially in agriculture where efficient water management faces challenges from limited resources. Anderson and French emphasize significant advancements in ET measurement and modeling that are applicable to diverse cropping systems. Traditional models, like FAO-56, rely on

outdated crop coefficients that do not reflect modern irrigation practices or crop varieties, particularly as high-value non-cereal crops are increasingly cultivated in varied environments, such as greenhouses. Recent studies featured in Agronomy explore innovative ET measurement techniques, including infrared thermometers for precise assessments in controlled conditions and neural networks utilizing data from economical meteorological stations, enhancing model accuracy without the legacy crop coefficients. For instance, evaluations of weighing lysimeters and eddy covariance methods demonstrate improved accuracy through synchronized energy budgets over shorter time frames. Additional studies investigate the effects of irrigation and crop management on ET, revealing negligible differences in water use efficiency for varying irrigation levels in drip-irrigated silage maize, alongside the ability to mitigate soil compaction impacts by maintaining sufficient moisture levels in faba beans. In wine grape production, salinity stress was found to not significantly heighten growth limitations beyond those caused by drought, challenging existing models. Additionally, the capabilities of multispectral sensors were shown to be comparable to those of hyperspectral sensors for assessing turfgrass water use, underscoring the ongoing need for adaptable observational tools across diverse agricultural landscapes. Collectively, this body of work reflects a shift towards more technology-driven and nuanced solutions for ET estimation, vital for optimizing agricultural productivity and addressing water scarcity in the context of changing climatic conditions.

4. The irrigation system, which is to, be used for Melbourne has a structure as shown in figure 1. This system will comprise of five components, which are interlinked in order to perform the task of irrigating the land. These include pumping station, field application, and distribution, conveyance, and drainage systems. The pumping station acts as the intake point for water from a river or reservoir to the irrigation system (Hao 2006). The water then flows to a conveyance system, which transports water to ditches that act as the distribution system. Water within the distribution system is then transported to the field application system. The field application system is characterized of sprinklers, which ensure effective distribution and use of water for all crops within the irrigation system. The irrigation system has a drainage system, which will enable in the removal of excess water.

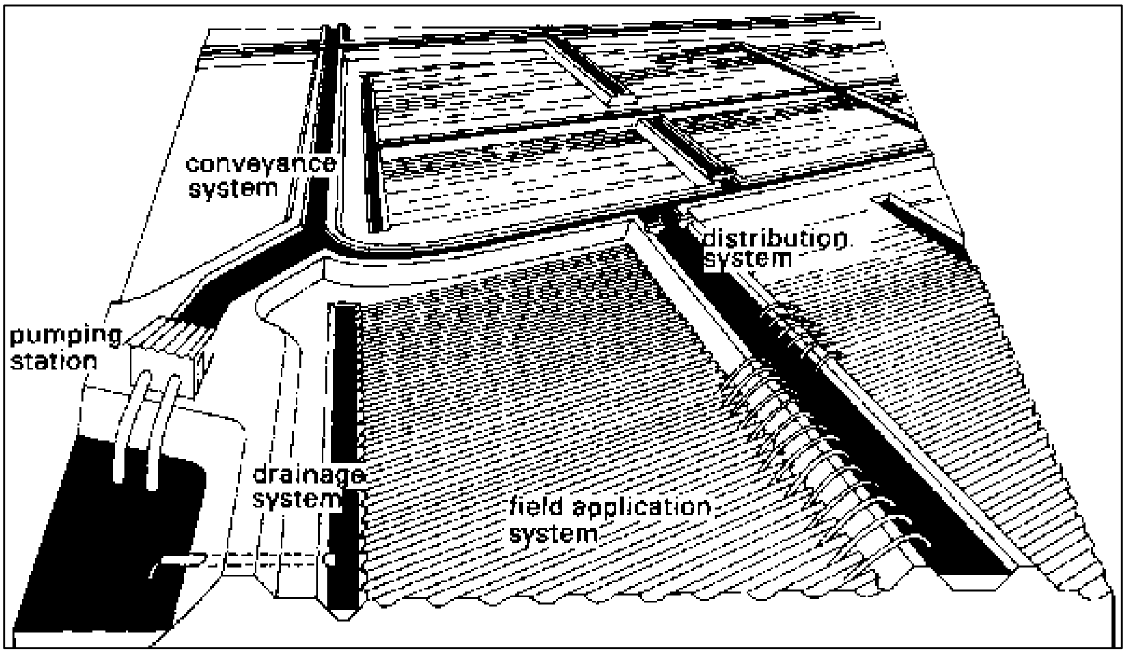

Figure 4.2: Irrigation System Source: Hao, S, 2006. Irrigation System.

5. This literature survey investigates the complex interactions between irrigation and evapotranspiration (ET), essential elements of the hydrological cycle, particularly amid challenges posed by global warming and water scarcity. Recent research highlights that irrigation not only meets crop water needs but also critically influences ET, including potential evapotranspiration (PET) and actual evapotranspiration (ETa). Through analyses of CNKI and Web of Science databases, the survey reveals key themes such as the incorporation of remote sensing (RS) technologies and machine learning in estimating ET and irrigation volumes. Findings indicate that while irrigation enhances soil moisture and crop yields, it concurrently disrupts regional climates by modifying soil temperature and precipitation patterns, resulting in decreased PET and increased ETa. Various methodologies for estimating ET, including RS, empirical models, and machine learning algorithms, are explored, emphasizing the necessity for high-resolution data to improve irrigation management and resource allocation accuracy. The analysis documents a significant shift in literature trends over the past two decades from crop-yield relationships toward a focus on irrigation's hydrological implications. This work underscores the vital need to comprehend the dynamic interplay between irrigation and ET for sustainable agricultural practices and effective water resource management, suggesting future research directions to investigate different irrigation methods and seasonal variations on ET while refining estimation models through

advanced technologies to tackle water scarcity challenges and enhance agricultural resilience

6. The review by Gong et al. examines the critical interactions between irrigation and evapotranspiration (ET) in the context of global warming and water scarcity. Through a comprehensive analysis of literature from the Chinese National Knowledge Infrastructure (CNKI) and the Web of Science (WOS), the authors highlight emerging research trends, indicating a growing focus on topics such as remote sensing technology, crop yield, and water utilization efficiency over the past two decades. The review emphasizes the essential role of ET in the hydrological cycle, affecting crop water demand, regional climate, and agricultural practices. Different methods for estimating ET and irrigation volume are discussed, noting advancements in remote sensing and machine learning techniques that enhance accuracy and application in various climatic conditions. The report underscores that irrigation not only meets agricultural water requirements but also initiates complex ecological and hydrological effects, such as groundwater recharge and climate modification. It concludes with a call for further research to elucidate the mechanisms through which irrigation influences ET, particularly in arid regions, and emphasizes the need for sustainable water resource management strategies. This survey serves as a valuable reference for future investigations into optimizing irrigation practices and adapting to climate-related challenges.
7. The study by Torres et al. investigates the impact of irrigation strategies utilizing varying fractions of crop evapotranspiration (ETc) on water productivity and flavonoid composition in Cabernet Sauvignon grapevines amidst climate change challenges, including reduced precipitation and increased temperatures. Conducted over two contrasting precipitation seasons, the study assessed irrigation treatments of 25%, 50%, and 100% ETc, revealing that irrigation effectively mitigated water scarcity, particularly when rainfall was insufficient. Notably, the 50% ETc treatment enhanced berry composition boosting total soluble solids, anthocyanin, and flavonol levels—without compromising yield and sustaining arbuscular mycorrhizal fungi (AMF) colonization rates, vital for grapevine health, while also reducing the vineyard's water footprint. The findings emphasize the need for efficient irrigation management by demonstrating that excessive watering is counterproductive and can adversely affect grape quality. Consequently, the research provides essential insights for viticulturists, advocating the development of irrigation schedules that not only adapt to future climatic conditions but

also minimize environmental impacts. Overall, balanced irrigation practices are shown to enhance water use efficiency and grape quality, supporting sustainable viticulture in semi-arid regions.

8. The paper by Stockle et al. (2023) critically examines the accuracy of actual evapotranspiration (ETa) estimations essential for effective irrigation scheduling by comparing three distinct modeling approaches: CropSyst-W, which integrates NDVI (Normalized Difference Vegetation Index) within a crop modeling framework; EEFlux, an energy balance model leveraging satellite data through Google Earth Engine; and OpenET, a community-driven platform synthesizing multiple model outputs. The study's findings reveal that CropSyst-W outperforms its counterparts, achieving a Willmott index of agreement (d = 0.93) and a lower normalized root mean square deviation (NRMSD = 0.31), compared to EEFlux (d = 0.77, NRMSD = 0.47). Various uncertainty factors were identified, including model parameterization and NDVI data accuracy, complicating ETa accuracy due to spatial variability and differences in crop development stages. The authors emphasize the importance of integrating sensor data into ETa models to improve irrigation scheduling, advocating for continuous advancements in model calibration, real-time validation, and the incorporation of high-frequency satellite imagery and UAV data for operational practices. This research significantly advances the discussion on irrigation management by revealing the strengths and limitations of existing modeling techniques and proposing innovative pathways for enhancing agricultural water use efficiency in the face of changing climate scenarios.
9. The importance of precise ET data is accentuated for efficient irrigation scheduling, especially under varying climate scenarios. The study identifies the need for ongoing improvements and emerging techniques in ET measurement. Technologies such as precision agriculture and remote sensing can play crucial roles in enhancing ET estimation and improving resource management.
10. Crop evapotranspiration irrigation is a strategic method designed to optimize water usage by leveraging the natural water consumption and evaporation rates of crops, informed by crucial factors such as crop type, developmental stages, and climatic conditions, including temperature, humidity, and wind speed. This approach enables real-time irrigation management through an irrigation control program that responds to specific water requirements, ensuring uniform water application across the irrigated area while minimizing the risks of under- or over-irrigation compared to traditional

methods like surface or sprinkler irrigation. Despite its advantages, including reduced infrastructure needs and energy savings, challenges such as emitter clogging and salt accumulation, particularly with saline water, necessitate continuous soil monitoring. The design of a successful irrigation system encompasses interconnected components including pumping stations, conveyance, and drainage systems, facilitating efficient water management through ditches and sprinklers. Additionally, the Crop Water Stress Index (CWSI) offers an alternative strategy by measuring canopy temperature to evaluate crop stress; however, it is primarily suited for commercial applications and does not provide precise water volume estimates, thus highlighting the unique strengths and limitations of the crop evapotranspiration irrigation strategy within the broader context of modern agricultural practices.

11. The study focused on optimizing water management for processing tomato cultivation in Southern Italy using the AquaCrop model, aiming to balance crop yield, water efficiency, and economic returns. It identified that an optimal irrigation depth of around 400 mm maximized performance indices while achieving good water efficiency, and a seasonal irrigation of 300 mm improved water savings without compromising yield. AquaCrop assessed various irrigation strategies, accurately simulating growth metrics such as canopy cover and yield through a calibrated and validated modeling framework. Although higher irrigation volumes improved yield, they adversely affected water use efficiency and environmental sustainability, with the best trade-offs found between 300 mm and 400 mm of seasonal irrigation. Ultimately, the study proposed a methodological framework that integrates economic and environmental considerations for irrigation strategy optimization, highlighting the importance of crop production models like AquaCrop in informed agricultural water management. This approach provides valuable insights for sustainable agricultural practices in Mediterranean climates, addressing water scarcity while ensuring profitability for farmers.
12. Evapotranspiration (ET) is a crucial component of the hydrologic cycle, representing the energy interaction among the hydrosphere, atmosphere, and biosphere through the processes of evaporation and transpiration. It significantly influences agricultural practices, particularly irrigation scheduling, as it governs water availability and crop yield, accounting for about 15% of atmospheric vapor. Effective irrigation strategies depend on precise ET measurements, which are affected by various environmental and meteorological factors, including crop geometry, growth stages, and weather conditions. Reference ET (ETo) serves as a standardized metric for atmospheric

evaporation demand and is vital for water management, especially in arid and semi-arid regions. Measurement techniques vary from highly accurate but labor-intensive lysimeters to energy balance and mass transfer methods. Numerous estimation models have been developed, from empirical approaches like Thornthwaite and Hargreaves-Samani to the highly regarded FAO-56 Penman-Monteith method. However, uncertainties persist in ET estimation due to climatic variability and data limitations, underscoring the need for ongoing research to refine methodologies and tailor ET models to local conditions, particularly in the context of climate change impacts on ET processes.

13. Climate change significantly influences ET through variations in temperature and precipitation, disrupting the water cycle. These changes pose challenges for agricultural practices, making it critical to assess water management strategies. The review emphasizes the relationship between climate variability and potential impacts on crop yield, highlighting the necessity for adaptive agricultural strategies.
14. The article evaluates agricultural water consumption and productivity differences in the Amu Darya and Syr Darya river basins, utilizing the SEBAL model to analyze data from 2000 to 2020. Key findings reveal that the Amu Darya area (IAAD) has an average evapotranspiration (ET) of 1150 mm, showing a declining trend, while the Syr Darya area (IASD) averages 800 mm, with an increasing trend attributed to more cultivable land. Notably, lower water productivity was observed in IAAD crops like cotton and rice, compared to higher productivity in IASD. The study confirmed a strong correlation ($R^2 > 0.7$) between ET from SEBAL and the Penman–Monteith method. Methodologically, it employed high-resolution satellite data and remote sensing to validate ET estimates and compare water productivity across crops. The conclusions emphasize the need for effective water management strategies and technological advancements in irrigation practices to address the Aral Sea crisis, while highlighting the importance of remote sensing in agricultural management in data-scarce regions. Overall, the article serves as a critical assessment of water management in delta regions adjacent to the Aral Sea, underlining the need to address evapotranspiration dynamics and productivity for environmental sustainability.
15. The publication provides a comprehensive overview of evapotranspiration (ET), a vital variable impacting agronomy, hydrology, and various physical sciences, which includes two key processes: transpiration—where plants uptake water and release it as vapor—and evaporation, and emphasizes the importance of accurately quantifying ET for

effective irrigation management in agriculture, particularly as water deficits can negatively affect crop growth and yield. Key factors influencing ET include climate, plant species, canopy characteristics, irrigation management, and soil attributes, whose interactions result in variability in ET rates. The document also outlines methods for estimating actual crop water use (ET) based on reference ET and crop-specific coefficients, which facilitate better irrigation practices, and discusses additional sources for obtaining ET data, such as weather stations and atmometers, underscoring the significance of localized measurements for improving irrigation efficiency. By understanding ET's dynamics, agricultural practices can be optimized, helping enhance water resource management and crop productivity amid changing climatic conditions and water availability.

16. The research explores various ET estimation methods, categorizing them into direct measurements and indirect models. Direct methods, such as lysimeters and eddy covariance, provide high accuracy; however, they come with high costs. Conversely, empirical models, like the FAO Penman-Monteith, offer a more accessible alternative but require local calibration for precision.
17. There are highly variable keywords in the analyzed documents which highlights the multidimensional and contemporary nature of ET_c research. The keyword with the highest number of occurrences was evapotranspiration (564) followed by remote sensing (219), crop coefficient (119), reference evapotranspiration (118), irrigation(96), eddy covariance (64), energy balance (55), moderate resolution imaging spectroradiometer (MODIS) (46), Penman-Monteith (45), and crop evapotranspiration (44) (Fig. 3a), suggesting that these are among the most commonly discussed areas in ET_c research. Most of these keywords appeared simultaneously three years after the publication of the FAO56 Penman-Monteith ET_o meth- od in 1998. Other authors who conducted bibliometric analysis on related topics such as sustainable water use in agriculture and water-use efficiency also reported a high frequency of the keywords evapotranspiration and irrigation (Abafe et al., 2022; Aleixandre-Tudó et al., 2019). Trend analysis further showed that keywords such as stomatal resistance and irrigation requirements were commonly used by researchers since the early 2000s and remain relevant to the present day. These two keywords are interconnected, with stomatal resistance playing a crucial role in assessing crop water status and estimating transpiration, which are essential for effective irrigation management (Cannavo et al., 2016). The period between 2008 and 2018 exhibited the

maximum diversification of authors' keywords, with many terms revolving around soil-plant-atmosphere interactions and decision support systems. Moreover, the term crop modeling paved the way for the emergence of new keywords such as machine learning, random forest, artificial intelligence, and goog- le earth engine which began to gain prominence starting in 2020 (Fig. 4.3,a,b,c).

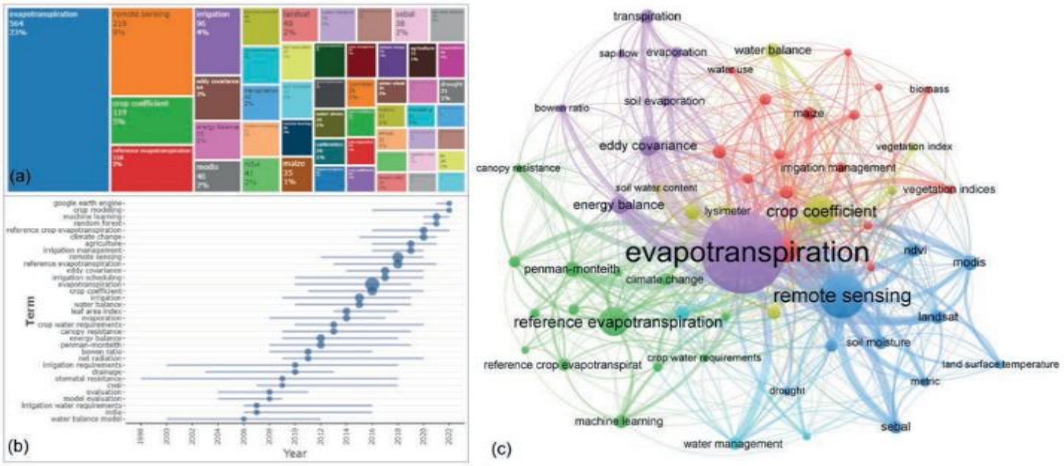

Figure 4.3: (a-b) Trend analysis and (c) co-occurrence network of author keywords

18. In conclusion, higher climate parameters are often associated with fluctuations in *ET* values and heat stress, thus disturbing the water cycle. The disturbance of the water cycle can highly influence water availability on Earth and pose an alarming situation for world agricultural production and economic development. Therefore, it is essential to understand the role of *ET* and its importance in maintaining and balancing water availability on Earth. Besides, accurate *ET* estimation information could help to improve and reduce the effects of future water crises for the agriculture sector under rapid CC (Tanny 2022). In addition, after irrigation, a particular share of applied water is withdrawn from the field through *E* and *T* processes to the atmosphere, and some returns to groundwater through infiltration. In this regard, irrigation water supply and demand improvements are mandatory to decrease WUE and crop production under current and future CC. Therefore, the proper irrigation application or schedule based on precise *ET* information (see Fig. 4.4) is considered the most effective water management practice and has significant economic and environmental impacts (Yan *et al.* 2018, 2021b). Besides, the average

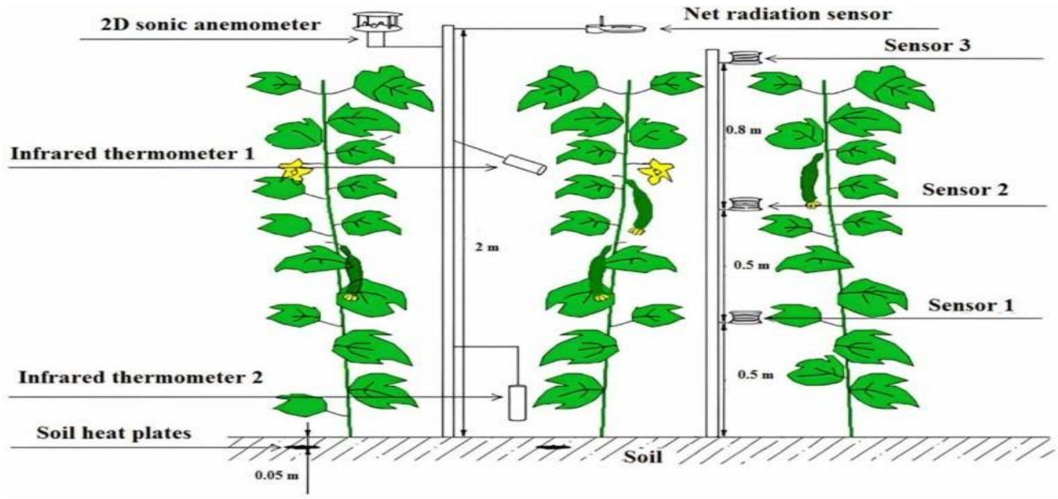

Figure 4.4: Estimating greenhouse cucumber transpiration using different sensors at different heights (Yan *et al.* 2020).

19. The importance of precise ET data is accentuated for efficient irrigation scheduling, especially under varying climate scenarios. The study identifies the need for ongoing improvements and emerging techniques in ET measurement. Technologies such as precision agriculture and remote sensing can play crucial roles in enhancing ET estimation and improving resource management.
20. Susantha Wanniarachchi and Ranjan Sarukkalige explores the critical role of evapotranspiration (ET) as a component of the water cycle and agricultural water balance. The authors emphasize that accurate ET estimation is essential for sustainable agricultural water management, highlighting its significance in resource planning, mitigating water scarcity, and improving water use efficiency. The review discusses various methodologies for estimating ET, including traditional techniques and modern advancements such as remote sensing, machine learning, and drone technology. The findings reveal that while ET measurement has evolved, challenges remain in integrating these technologies effectively into practical applications. Furthermore, the paper highlights the necessity for accurate ET estimation to optimize irrigation practices, especially in the context of climate change, which is projected to exacerbate water shortages and increase evaporation rates. The authors advocate for further research into innovative ET measurement tools and the integration of precision agriculture techniques to enhance agricultural water management. This systematic review ultimately underscores the importance of improving the accuracy of ET estimation to achieve sustainable agricultural practices and ensure food security amidst growing water-related challenges.

21. Each ET estimation method has its strengths and limitations. While direct measurement techniques yield reliable data, their prohibitive costs restrict wide-scale application. On the other hand, models that are less costly often lack accuracy unless tailored to local conditions, emphasizing the need for thorough calibration.
22. Water scarcity poses a significant challenge to global agricultural productivity, warranting the need for enhanced water use efficiency (WUE) strategies. This review synthesizes literature on various management options to improve WUE in crop production, as agriculture remains the largest consumer of water, contributing significantly to total evapotranspiration. Several approaches have been identified to enhance WUE, including the incorporation of crop residues, which improves water retention and soil moisture while increasing yields by 13-25%. Additionally, the application of organic fertilizers enriches soil quality, aiding moisture conservation and nutrient availability. Inter cropping strategies allow for complementary interactions between crops, further optimizing resource utilization and enhancing WUE. Collectively, these findings indicate that a multifaceted approach incorporating practices like crop residue return, organic amendments, and strategic inter cropping can significantly improve agricultural water efficiency, thereby paving the way for sustainable agricultural practices and improved food security in the face of escalating water scarcity.
23. The research comprehensively reviews various methods for estimating evapotranspiration (ET) and their relevance within climate-smart agriculture (C-SA). It highlights the roles, challenges, and applications of these methods, particularly under the impacts of climate change. As climate dynamics evolve, understanding ET becomes essential for effective water resource management and crop productivity.
24. The literature review focuses on the estimation of crop evapotranspiration (ETc), emphasizing its critical role in sustainable agricultural water management. This bibliometric and thematic analysis encompasses 1,872 documents retrieved from the Web of Science™ covering the period from 1987 to 2022. Key findings reveal that research is predominantly driven by institutions from the USA and China, with the journal Agricultural Water Management being the most prolific in terms of publications and citations. The analysis identifies a broad range of topics within ETc, particularly highlighting the importance of remote sensing and machine learning technologies. Despite the growth of literature, significant gaps remain in the study of ETc and reference evapotranspiration (ETo), necessitating enhanced collaboration and research

in regions experiencing water scarcity. Future investigations should leverage new methodologies, including machine learning, to better understand climate change impacts on ETc and improve irrigation management practices. Moreover, the resurgence of interest in ETc research indicates a continuous evolution of the field, underscoring the need for ongoing updates to theoretical frameworks and practical applications.

CONCLUSION

The ongoing advancements in ET estimation methods are vital to developing effective climate adaptation strategies. By ensuring accurate water management practices, these methods contribute to food security and the sustainable use of water resources amid climate change. Addressing existing challenges in local calibration and adopting innovative technologies will be crucial for maximizing the benefits of ET estimation in agricultural settings.

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