Evapotranspiration Measurement

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Detailed knowledge of energy and mass fluxes between land and the atmosphere are necessary to monitor the climate of the land and effectively exploit it in growing agricultural commodities. One of the important surface land fluxes is evapotranspiration, which combines the process of evaporation from the soil and that of transpiration from plants, describing the movement of water vapour from the land to the atmosphere. Accurately estimating evapotranspiration in agricultural systems is of high importance for efficient use of water resources and precise irrigation scheduling operations that will lead to improved water use efficiency.

Keywords: evapotranspiration ; greenhouse ; agriculture ; energy ; water ; food ; nexus

1. Introduction

The global increase in food demands pressures food systems to increase yields despite limitations in water resources. As such, there is an impetus to move to more sustainable practices and optimised operations for agricultural systems that will enable efficient use of water resources [1]. A key aspect for efficient agricultural practices is adequate irrigation management, which depends on accurate estimates of crop water requirements. Evapotranspiration (ET) is a measure of crop water requirements, which entails vapour water movement from the land to the atmosphere in the form of evaporation from the soil and transpiration from the plants [2]. Hence, the appropriate evaluation of evapotranspiration is necessary to prevent excess or deficit irrigation and sustain the use of water resources while offering the necessary agricultural commodities. This can be achieved through models that measure and predict evapotranspiration rates, or direct measurements using high-performing instruments. Challenged by the complexity and high cost of directly measuring evapotranspiration, numerous efforts have been deployed in developing estimation models that can easily be applied to varied applications and growing mediums [3].

The accurate estimation of crop water requirements is of high importance in the agricultural sector as it aids in the optimal operations of irrigation scheduling in terms of frequency and quantity. Knowledge of evapotranspiration rates can hence support growers to meet their cultivation targets, improve water use efficiency, increase crop yields, reduce energy consumption, and reduce associated environmental emissions [4]. This indicates apparent intertwined interlinkages between the energy water and food (EWF) systems that are driven by ET estimates and measurements. The EWF nexus is a holistic approach that aims to evaluate the inherent interdependencies between the energy, water and food systems, and identify trade-offs and synergies between their resources [5]. Through this, the EWF nexus approach enables the optimisation of resource consumption and the reduction of associated system environmental burdens [6][7][8]. Thus, it is necessary for agricultural food systems to adopt an EWF nexus methodology to ascertain a sustainable intensification that can meet the growing population demand for nutritious food, conserve water and energy resources, and preserve the environment from further degradation [9].

With regard to evapotranspiration models, the first ET model was developed by Penman, in which only external physical drivers were considered [10]. This latter model was further improved by Monteith, who integrated physiological characteristics [11]. Other simplified versions of the Penman–Monteith equation were proposed, which require less input data [12]. Since these models have been developed under specific meteorological and physiological conditions and for specific settings (i.e., open or closed fields), it is necessary to choose the model with the closest conditions and assumptions as the system under study. Moreover, adapting these models to the specific growing conditions of the evaluated system can enhance the accuracy of ET estimates. This can be achieved through the parametrisation of observed relationships through direct measurements [13]. The vast majority of reviews conducted around evapotranspiration address the main differences between certain empirical ET models in terms of input data, accuracy, and limitations [3][14][15]. Others only reviewed specific measurement techniques such as remote sensing or for assessing certain parameters such as the leaf area index [16][17]. However, there is a lack of studies that discuss the applicability of ET models to open and closed agricultural mediums, and that provide methods and directions for ET estimate improvement through direct measurements. As such, this review aims at responding to this gap by aggregating ET models and measurement methods in one study, and evaluating their applicability for different agricultural settings as well as discussing ET estimates from an EWF nexus perspective.

2. The Role of Evapotranspiration Measurement in Optimising the Energy, Water and Food (EWF) Nexus

The continuously growing population and the rising economic growth engender many challenges in securing the intensified energy, water and food demands. The intertwined dependence between the energy, water and food sectors makes it imperative to adopt a holistic nexus approach in confronting these challenges [5]. Water is a crucial subsystem of the EWF nexus through which the supply of energy (e.g., hydropower), water, and food (e.g., agricultural irrigation) is attained. Therefore, the adequate assessment and forecasting of water quantities in these different sectors are of high importance [18]. The agricultural sector accounts for 3.5% to 4.8% of the total energy consumption, and 70% of the total freshwater withdrawals. It is predicted that demand for food will increase by 60% by 2050, which will lead to an increase of more than 50% of the irrigation water requirements. With this in mind, improved irrigation practices are indispensable to overcome challenges related to food security [19][20].

Critical nexus interactions are found in the supply of irrigation water requirements for agriculture. Water and energy subsystems are closely intertwined through the use of direct energy for pumping fresh water and desalinating water for irrigation. Inaccurate measurements of irrigation water requirements will thus lead to inefficient use of energy supplies [20]. Agricultural systems also consume indirect energy in the form of fertilisers, which defines a crucial energy-food nexus [21]. For example, increased food prices have been linked to spikes in fertiliser and fuel prices [19]. Thus, the type and amount of fertilisers required in agricultural systems need to be carefully assessed, monitored, and planned since assimilation of nutrients by plants varies with respect to soil moisture content and transpiration. Moreover, in cases where ET is overestimated, excess irrigation may lead to the leaching of nutrients to groundwater systems.

Nutrients and water, that have a close interaction, are directly responsible for the growth of plants and can either achieve positive or negative outcomes depending on their amounts and balance. Adequate irrigation treatments aid in nutrient availability and their transformation into useful consumable forms. The mineralisation process of organic nitrogen present in soils or from fertilisers is highly dependent on soil moisture amongst other parameters. The mineralised nitrate product from the nitrification of ammonium increases with an increased available water content within a tolerable range as it is greatly vulnerable to leaching losses. Hence, an adequate soil moisture content is required to ensure the nitrification of ammonium, whereas an excess or a deficiency in water content restrains this process [22]. Low soil moisture can affect the amount of nutrient uptake by the plants such as sodium, potassium, calcium, magnesium, zinc, etc. This can lead to reductions at the level of the total dry weight of leaves, stems and fruits for avocado plants [23]. On the other hand, and for the same type of plant, excess soil moisture can also lead to severe repercussions on the plants associated with decreased concentrations of iron and zinc at the level of the leaves [23][24]. In accordance with these findings, citrus plants have also witnessed reductions in nutrient intake when subject to excess soil moisture content or excess irrigation regimes. Concentrations of calcium, magnesium and iron dropped in the citrus seedling leaves when soil moisture was in surplus [25]. The close interaction between nutrient efficiency and water supply makes it imperative to not only define the nutrient ratios and amounts and set their schedule but also to adequately estimate the necessary irrigation water and closely monitor its supply [22].

Calcium deficiency in plants is another consequence of low or high water availability and transpiration rates. Calcium is a nutrient that is transported via the xylem and not the phloem of the plant, which makes its movement in the different parts of the plant primarily driven by transpiration that induces a suction action to draw water and nutrients up. A high surface-to-volume ratio in fruits is an important parameter that promotes transpiration and thus helps calcium transport and its accumulation in fruits. However, as the fruit grows and becomes larger, its surface-to-volume ratio decreases and more wax deposition occurs which reduces transpiration rates. This means that as the fruit grows, it is more likely to witness reduced calcium flow into the fruit [26]. It has been proven that improving plant transpiration is more effective in solving calcium deficiencies in fruits than directly increasing calcium levels in the substrate [27]. Moreover, the effect of climate parameters, namely low solar radiation and high humidity, have been linked to calcium deficiencies in tomato plants perceived in leaf damage and reduced yields. These latter parameters drive the evapotranspiration rate which needs to be assessed in advance to predict climate variabilities and minimise their impact on crop growth and yield. In this particular study, humidity levels need to be lowered in the food system to balance the high solar intensity and enhance transpiration rates [28]. In this case, accurate estimations of transpiration will help control the flow of calcium throughout the plant and counterbalance the effect of climate stressors. Other studies revealed that excess transpiration rates were responsible for calcium deficiencies in low-transpiring species such as cauliflower, lettuce and cabbage plants. The high transpiration rates caused high calcium transport to the outer leaves at the detriment of the inner leaves to receive equitable amounts of calcium [29].

Upgrading agricultural food systems often comes at the expense of higher water and energy supply. Agricultural greenhouses are a good example of yield improvement systems, that provide a closely controlled microclimate. Temperature and humidity are some of the main microclimate parameters that can be controlled and monitored through the deployment of adequate technology systems (e.g., heating, cooling, and ventilation) which require substantial amounts of energy for their operation. These parameters are crucial drivers of plant evapotranspiration rates and thus irrigation requirements [30][31]. CO_2 enrichment is another yield improvement and water reduction practice in agricultural greenhouses. CO_2 can be procured either through purchasing commercial or industrial CO_2 or internally producing it using gas burners. This induces additional energy requirements and expenditures to greenhouse operations [32]. The effect of higher CO_2 concentrations has been witnessed in evapotranspiration reductions due to the shrinking of stomata openings in plant leaves which control gas exchange between the plant and atmosphere (i.e., water vapour and CO_2). Thus, it is important to account for this parameter in evapotranspiration estimates and irrigation water requirements [33][34]. Not assessing evapotranspiration based on the new microclimate settings will lead to the inefficient use of these technologies and the wasteful utilisation of energy and water resources.

3. Evapotranspiration Measurement Techniques

3.1. Leaf Area Measurements

Leaf area index measurement techniques are divided into two main categories: direct and indirect. The direct measurement systems entail destructive approaches from harvesting leaves. Indirect leaf area measurement systems are non-destructive techniques through which the leaf area is estimated by assessing how the canopy intercepts radiation [35]. Leaf area estimates are important because they reflect the transpiring surface size. This estimate can be integrated into the models discussed previously to depict variations in the internal resistance and net radiation within the multi-layered canopy. Ceptometers are a cost-effective tool that draws an estimate of the leaf area index (LAI) by measuring the photosynthetically active radiation (PAR) above and below the canopy. Several studies investigated the accuracy of the ceptometry technique against destructive methods and concluded that it provides good accuracy for LAI measurements of uniform canopies [36]. Another tool for indirect LAI measurement is via hemispherical photography. This technique involves the study of canopies via fisheye shaped lenses located downward (looking up) or upward (looking down) the canopy. It provides information about the size, density, position and distribution of gaps detected in the canopy. However, this technique necessitates extensive post-processing of each image independently which can lead to errors [17][37]. The leaf area meter such as the LAI-2200C proposed by Licor is another technique, which measures the interception of blue light from below and above the canopy [37]. Image-based remote sensing techniques can also be considered as an indirect measurement of LAI, which are based on estimating LAI from empirical relations between LAI and vegetative indices [38].

3.2. Leaf Temperature Measurements

Estimating surface leaf temperature can enhance model-based estimates of ET rates. Leaf temperature and the temperature gradient between the leaf surface and the ambient directly impacts the rate of transpiration. Under ideal conditions, the temperature at the leaf surface is lower than that of the ambient. The opposite, either higher leaf temperature or equal to the ambient, is an indication of crop stress and unsuitable growing conditions. Hence, it is crucial to have an estimate of surface leaf temperature as it defines the saturation water vapour concentration within the stomata which represents an indication of gas exchange between the leaf and the atmosphere [39]. Thermocouples are thermoelectric systems based on converting a temperature signal into an electric signal. The main advantages of this system are its low cost, simple operation, light weight, and fast response as compared to other more complex measurement techniques [40]. However, the main disadvantage of this system is the direct contact with the leaf surface, in which the thermocouples can absorb solar radiation and heat from the leaf by conduction. These problems lead to significant errors in leaf temperature estimates [41]. Infrared thermometers are also used for leaf temperature measurements and consist of infrared temperature sensors that measure the infrared energy emitted by a specific spot on the leaf surface and transform it into a measurable electrical signal. The major advantages of this method, apart from being contactless, are quick response and high accuracy. However, the infrared method is sensitive to the environment in which dust and steam can significantly influence its precision [40]. Thermal infrared imaging is another leaf temperature measuring system that contains an optical system and is considered a remote sensing technology. This system entails temperature measurements at multiple points on the leaf surface, as opposed to spot infrared thermometers. The infrared camera uses infrared detectors that are sensitive to wavelengths between 7–14 μm to capture infrared energy and converts it into two-dimensional thermographic image visualisations. These cameras are able to evaluate temperature gradients over large temporal and spatial scales contrary to thermocouples, which can help identify variations in ET across large crop areas. Impacts of some parameters such as the leaf surface emissivity and the longwave radiation can engender some inaccuracies in temperature measurements. Although most integrated software accounts for a correction factor for these variables, it is mostly based on indoor controlled conditions such as in laboratory settings. Some software can also have fixed corrective factors which cannot be changed by the users depending on their outdoor conditions. Other software can combine user-inputted corrective parametrisations, however, it is usually challenging to estimate these factors due to the complex settings and dynamic environmental variables [42]. Moreover, thermal cameras hold high acquisition costs, which limit their use in agricultural applications [40].

3.3. Eddy Covariance Systems

The eddy covariance is considered as one of the techniques for the direct measurement of evapotranspiration. The eddy covariance is comprised of two sections: an anemometer that directly measures wind speed and direction, and an infrared gas analyser (IRGA) that measures gas concentrations in the air such as water vapour. The simultaneous evaluation of changes in vertical air velocity and water vapour concentration in the air is what enables the measurement of evapotranspiration in the form of a vertical flux of water vapour. The eddy covariance technique has been applied to open field applications including field crops, forests, water bodies, and grasslands, etc. [43]. The eddy covariance method entails challenging operations as it involves high-frequency measurements along with complex processing of simultaneously collected data. Moreover, the validation of ET estimated by this system with other methods is quite challenging due to the large scale, highly variable area and open boundary layer of the volume studied which does not achieve energy balances [44].

3.4. Weighing Lysimeters

Weighing lysimeters directly measure evapotranspiration by evaluating changes in the mass of the soil and crop. They necessitate that the soil structure and composition, the physiological characteristics of vegetation (e.g., height), and the climatic conditions of the growing medium inside the lysimeter are similar to the ones outside the lysimeter. The high economic cost and intensive installation and maintenance requirements of lysimeter systems limit its application on various parts of the agricultural system to perceive spatial evapotranspiration variations, which restricts measurements to be taken on only one or few parts of the land under study. However, a significant advantage of lysimeters is that they provide simultaneous information on percolation of excess irrigation and soil-water retention that no other methods provide [44].

3.5. Gas Exchange Measurement Systems

Gas exchange measurement systems enable direct and accurate estimates of ET rates by tracing the absorption of gases through an infrared light source (infrared gas analyser IRGA). The latest advancements of these systems operate under open chambers that evaluate differential gas exchanges through estimating the difference in gas concentrations (i.e., H_2O and CO_2) between the input and output of the chamber [45]. These systems can also estimate CO_2 exchanges at the stomata level, which can be crucial in estimating the impact of increased CO_2 concentrations in the air on the internal resistance and on the evapotranspiration levels [46]. Higher CO_2 concentrations can be caused by increased greenhouse gas emissions or linked to CO_2 enrichment practices in greenhouse settings. Particularly in the latter application, evaluating the effect of varying CO_2 concentrations is of high importance to determine the ideal CO_2 concentration that needs to be injected for optimal outputs in terms of yield and evapotranspiration levels [47].

3.6. Remote Sensing

Remote sensing revolves around the observation and measurement of parameters without physical contact with the subject under study. Remote sensing data can be retrieved from satellite technologies and provide information about biophysical parameters that can assess evapotranspiration such as the type and density of the vegetation and the surface albedo [16][48]. Several approaches have been developed in the literature for estimating evapotranspiration from remote sensing data, from which two general methods have been widely used in the agricultural field. One method uses radiometric surface temperature to separate latent heat from sensible heat. The second approach is based on vegetation indices (VI), taken from surface reflectance, that can estimate basal crop coefficients on spatial scales. Vegetation indices from satellite remote sensing include leaf area index (LAI) and the normalised difference vegetation index (NDVI) which can be included within the surface resistance estimation in the Penman–Monteith model [49][50]. The radiometric temperature can be adjusted to determine aerodynamic temperatures through semi-empirical or empirical models that incorporate spatial distribution in surface roughness lengths. This can be included in the Penman–Monteith equation to estimate ET rates. As for the basal crop coefficient, it can be used to estimate crop evapotranspiration from the reference evapotranspiration [49][51]. ET estimates from remote sensing data offer a large spatiotemporal distribution, which makes it a prevailing method in large scale and climate impact mapping applications [52]. However, challenges remain to obtain reliable estimates in regions with cloud cover and dust. Various studies tackled the reconstruction of missing data in these regions by means of different methods such as cloud removal and gap filling, but the linearity of these models still poses some limitations [53]. Remote sensing data are also used in data-driven models which estimate evapotranspiration rates by different data forcing methods such as machine learning, regression, neural networks, etc. The data-driven models can also be coupled with physical models to parametrise certain subprocesses dealing with uncertainty [54].

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