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COMMENTARY

The apples and oranges of reference and potential evapotranspiration: Implications for agroecosystem models

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Abstract

Although standardized evapotranspiration (ET) methods have been available for decades, they are commonly misunderstood, miscommunicated, and misused, especially within the agroecosystem modeling community. Some models misapply or misname standardized ET methods unbeknownst to users, and there is confusion in communication between applied ET practitioners and agroecosystem modelers. By highlighting some of these issues, we demonstrate and suggest the need for improved and consistent communication and application of standardized ET methodology.

1 | INTRODUCTION

Standardization has been an important practice in science and industry since the early manufacturing developments in the 18th century and currently affects our daily lives in innumerable ways. Standardization impacts everything from hand tools and machinery to electrical connections and software to the format required to write this paper. Compatibility, repeatability, quality, and effective communication are a few of the desired outcomes of standardization, which are all crucial goals in the fields of science and engineering.

However, standardization applied to biophysical processes such as evapotranspiration (ET), defined as the movement of water from land and plant surfaces (evaporation) and through plant surfaces, particularly stomata (transpiration), is difficult due to the complexity of biological and physical systems.

Abbreviations: AgMIP, Agricultural Model Intercomparison Project; ASCE, American Society of Civil Engineers; DSSAT, Decision Support System for Agrotechnology Transfer; ET, evapotranspiration; FAO, Food and Agriculture Organization of the United Nations; FAO-56, FAO Irrigation and Drainage Paper 56.

Nonetheless, standardization of ET terminology, principles, and methods has been essential to facilitate ET understanding, establish a common language for ET communication, and provide an ET benchmark among the diverse ET estimation methods available. Modern crop ET standardization efforts have culminated in several premier documents, one of the earliest being FAO-24 (Doorenbos & Pruitt, 1977), which "almost singly converted ET estimation practices worldwide to the use of reference ET and reference ET-based crop coefficients" (Jensen & Allen, 2016, p. 10). This idea promoted the use of daily crop coefficients (K_c), which scale crop ET (ET_c) from a reference ET (ET_{ref}), using the following equation:

$$ET_c = ET_{ref} K_c \quad (1)$$

This method has many advantages; namely, it separates the biological and physical components of ET, which are, respectively, estimated on the basis of the biological limitations of the plant canopy (K_c) and the physical demands of the atmosphere according to characteristics of a reference surface (ET_{ref})—this is also a simple approach relative to other ET models. More detailed methodologies further expand the K_c term into coefficients for transpiration (K_{cb}), transpiration reduction due to water stress (K_s), and evaporation (K_e). Chapter 2 of *Crop evapotranspiration: Guidelines for computing crop water requirements*, FAO Irrigation and Drainage Paper 56 (Allen et al., 1998) (hereafter referred to as FAO-56) later recommended the FAO Penman–Monteith equation as the sole method for calculation of ET_{ref} based on the "grass" (now "short crop") reference surface (ET_o), which requires solar irradiance, air temperature, air humidity, and wind speed as inputs. The authors explained that "the use of older FAO or other reference ET methods is no longer encouraged" (p. 18). This advice was later slightly amended to more explicitly define the Penman–Monteith equation for both a short and tall reference crop (ET_{os} and ET_{rs}, respectively), which encompassed the two most commonly used reference surfaces worldwide. The amended ET_{ref} equation was termed the "ASCE Standardized Reference Evapotranspiration Equation" and remains the current recommendation for ET_{ref} computation (ASCE, 2005). While there was concern "that use of the terms standard or benchmark may lead users to assume that the [ASCE] equation is intended for comparative purposes" (pp. 2–3), the Task Committee that drafted ASCE (2005) emphasized that the objective of the publication was "to establish a methodology for calculating uniform ET estimates and thereby enhance the transferability of crop coefficients and the comparison of ET demands in various climates" (p. A-2). Much of this history, theory, and application has been consolidated and updated in the recent edition of ASCE Manual 70, *Evaporation, Evapotranspiration, and Irrigation Water Requirements* (Jensen & Allen, 2016). In the long history of this methodology (Eq. 1), K_c models for dozens of crops have been developed for many environments around the world, many based on data from lysimetry, which is considered the gold standard for ET field measurement when properly designed, constructed, and managed.

Core Ideas

- Standardized evapotranspiration (ET) methods have been available for decades.
- Misuse of ET methods and nomenclature is common.
- Many agroecosystem models do not fully incorporate standardized ET methods.
- Standardized ET methods have been beneficial for model development and improvement.
- Consistent communication and application of standardized ET methods is encouraged.

2 | THE PROBLEM WITH POTENTIAL EVAPOTRANSPIRATION

Prior to the development of standardized reference ET and crop coefficient methods, efforts focused on estimating "potential ET" (e.g., Jensen, 1968). Potential ET (ET_p) was loosely defined by Jensen and Allen (2016, p. 19) as "the rate of ET that can occur when all soil and plant surfaces are wet"; however, "[b]ecause all soil and plant surfaces do not remain wet for long periods of time, ET_p, a term once used to describe the maximum rate of ET, has limited applications." Potential ET by definition is inherently different than reference ET; reference ET calculations apply only to the specific conditions of the two nonstressed, standardized reference surfaces (ET_{os} or ET_{rs}), whereas potential ET applies to any constantly wetted surface and does not have a single standardized definition (i.e., several equations can apply). Nonetheless, the two quantities are often confused and wrongly used interchangeably. An obvious problem is that crops with layered canopies (e.g. maize [*Zea mays* L.]) have short crop $K_c > 1.0$, resulting in $ET_c > ET_o$ (Eq. 1). Thus, although the concept of potential ET is not itself inappropriate, describing ET_{ref} (i.e., ET_{os} or ET_{rs}) alone as potential ET is highly inappropriate. Modern preeminent publications (i.e., Allen et al., 1998; ASCE, 2005; Doorenbos & Pruitt, 1977; Jensen & Allen, 2016) have consistently adopted ET_{ref} (with appropriate crop coefficients) for ET estimation because potential ET is difficult to universally define. Jensen and Allen (2016, p. 20) explained that ET_{ref} was designed "to address some of the ambiguities associated with definitions for potential ET and to serve as a consistent climatic index for ET. The term ET_{ref} has become the standard to characterize climatic effects on the ET rate. When estimating ET, the effects of crop cover, such as leaf area, and stage of growth, such as maturation, are related to ET_{ref} by a factor that varies with crop development. This factor is typically referred to as the crop coefficient, or the crop coefficient curve."

3 | EVAPOTRANSPIRATION ISSUES IN AGROECOSYSTEM MODELS

Although the standardized ET methods have been in development for decades and are now commonly accepted and used by applied ET practitioners (e.g., irrigation engineers, hydrologists, field researchers), the developers of agroecosystem models typically have not fully incorporated these methods into their models. Agroecosystem models, which aim toward holistic and comprehensive simulation of cropping system processes, also have a lengthy development history. Many models were initially conceived at a time when potential ET was the main, if not only, method available for ET estimation. Also, model developments have typically occurred in small research camps, each spearheaded by one (or a few) prominent scientist(s) with divergent goals, stakeholders, and funding sources. Efforts to develop standardized algorithms among various models have been unsuccessful, lax, and nonexistent. Some model developers (White et al., 2013) have described the need for standardization: "Efficient interchange of data among researchers, especially for use in simulation models and other decision support tools, requires use of a common vocabulary and strategy for organizing data." Even so, this idea as described pertains to standardizing language and units for model input and output data rather than model algorithms or evaluation techniques.

As one example, the agroecosystem model most commonly used by the authors of this article is the DSSAT-CSM (Jones et al., 2003), which claims over 14,000 users in more than 150 countries worldwide (www.dssat.net/about). The model primarily bases ET computations on a calculation of potential ET, which is partitioned into potential evaporation and potential transpiration components using an exponential function of leaf area index (Hoogenboom et al., 2019). Potential ET is calculated using either (a) a Priestley and Taylor (1972) approach or (b) the Penman–Monteith grass reference equation as described in FAO-56 (Allen et al., 1998). Priestley–Taylor is an appropriate method to compute potential ET, as Table L-2 in Jensen and Allen (2016) describes it as applicable to "large rain-fed land areas following regional rains." However, the Penman–Monteith equation is a reference ET approach, which therefore requires that its estimates be paired with appropriate crop coefficients for reasonable ET computations. Some DSSAT communications have named the model's potential ET outputs using reference ET terminology (i.e., "ET_o") and incorrectly suggested that ET_o can be partitioned into potential evaporation and potential transpiration (Hoogenboom et al., 2019) without first adjusting ET_o using appropriate crop coefficients. Furthermore, in the DSSAT code, interfaces, and publications (Hoogenboom et al., 2019), and even in several of our own scientific publications (Adhikari et al., 2016; DeJonge et al., 2012b; DeJonge, Andales, Ascough, & Hansen, 2011; DeJonge, Ascough, Ahmadi, Andales, & Arabi, 2012a; Kimball et al., 2019; Kothari et al., 2019; Marek et al., 2017; Modala et al., 2015; Sharda et al., 2019; Thorp et al., 2010), the Penman–Monteith method in DSSAT has been termed as "FAO-56" or "the FAO-56 method." This DSSAT ET method was formulated based on Equations 3–5 (p. 17–23) from FAO-56 (Allen et al., 1998) to calculate grass reference ET based on the Penman–Monteith combination equation (Equation 3); however, the DSSAT formulation ignores the rest of the 300-page FAO-56 document, including the FAO Penman–Monteith reference ET equation (Equation 6) and the crop coefficient methodologies described throughout the remaining pages. Because of these omissions, naming this DSSAT ET method as "FAO-56" or "the FAO-56 method" is a misnomer, as DSSAT fails to implement the Penman–Monteith reference ET formulation with appropriate FAO-56 crop coefficients (DeJonge & Thorp, 2017). Instead, the model (a) assumes reference ET is potential ET for some crops (but increases the value using a DSSAT-specific crop coefficient equation for other crops) and (b) uses an energy extinction coefficient method to separate potential ET into potential evaporation and potential transpiration (Hoogenboom et al., 2019), rather than calculation of K_c or any type of proper crop coefficient as described in FAO-56 (DeJonge & Thorp, 2017). While some may view the differences as nuanced, the "FAO-56" ET option in DSSAT is simply not the method described by FAO-56 (Allen et al., 1998). In consequence, the DSSAT method for some crops (e.g., maize) limits potential ET to the Penman–Monteith estimate alone (K_c = 1.0 as shown in DeJonge & Thorp, 2017), while FAO-56 suggests these values can be 20% higher than Penman–Monteith-based short crop reference ET (K_c = 1.2 in Table 12 of Allen et al., 1998). This misrepresentation in DSSAT has misled each of the authors independently and likely continues to mislead other model users, particularly those who are educated on the FAO-56 document of Allen et al. (1998).

The issues with DSSAT-CSM motivated DeJonge and Thorp (2017) to program a separate ET option in the DSSAT code that followed the ASCE (2005) Standardized Reference ET Equation, where the FAO-56 dual crop coefficient approach was used to establish the DSSAT-required estimates of potential evaporation and potential transpiration for non-stressed conditions. The effort led to several discoveries on the model's ET behavior, including identifying a wind transfer error in the DSSAT "FAO-56" subprocedure and demonstrating that the misnamed DSSAT "FAO-56" method was unresponsive to expected ET spikes from rainfall or irrigation while under full canopy. While supported by some, the effort has been contentious, with some modelers continuing to defend the original "FAO-56" formulation in the DSSAT model. This response has been unfortunate considering that the original purpose of standardized ET development was to codify language for common ET communication, with an aim to reduce contention among ET scientists.

The findings of DeJonge and Thorp (2017) led to several recommendations for the agroecosystem modeling community. First, modelers must understand the difference between potential ET and reference ET and apply the techniques correctly in their models. For example, if a model requires a calculation of potential ET, it should never use a reference ET alone without first applying the appropriate crop coefficients for non-stressed conditions. Reference ET indeed can be used to determine potential ET; see, for example, the method developed by DeJonge and Thorp (2017). The details are nuanced but important —we are not suggesting to abandon the concept of potential ET. Rather, when an estimate of potential ET is required, we are advocating for proper use. For example, well-defined potential ET methods such as Priestley–Taylor may be used alone, but if an ET_{ref} method is used to determine potential ET it should be applied with appropriate crop coefficients. Second, communications should accurately describe the ET methodology used. For example, the current "FAO-56" method in DSSAT is inappropriately named because the methodology is not fully consistent with the methods described in FAO-56. A major concern is that such misnomers can mislead scientists and proliferate incorrect information through scientific literature, which is counterproductive to ET standardization efforts. Third, the standardized ET methods (Allen et al., 1998; ASCE, 2005) can be applied to improve agroecosystem models in diverse ways, including (a) by programming standardized methods as a separate ET option in the model, (b) by using a stand-alone FAO-56 algorithm to benchmark ET time series from model simulations, and (c) by considering model ET output through the lens of crop coefficients ($K_c = ET_c/ET_{ref}$). These techniques have been used to evaluate ET measurement systems for decades and have similar potential to evaluate and improve agroecosystem models. Efforts to understand and use proper communication regarding standardized ET concepts is a first step toward these goals.

The impetus for this article was the recognition that ET terminology used in scientific communications remains inconsistent and often inaccurate. For example, in a recent call for abstracts for the 2nd ASABE Global Evapotranspiration Symposium (https://www.asabe.org/Events/The-2nd-ASABE-Global-Evapotranspiration-Symposium), the submission topic named "ET modeling and decision support system" was listed with the following subtopic: "Estimate actual ET from potential ET (Crop Coefficients)." This topic name is misleading and inaccurate because crop coefficients are used to estimate actual ET from reference ET, not from potential ET. The topic name is indicative of how inaccurate nomenclature and associated understanding of ET concepts has proliferated through the ET community, manifesting even in the topical session names of an international ET symposium.

The importance of properly communicating standardized ET terminology was further highlighted in a recent interaction during an oral presentation at the ASA-SSSA-CSSA International Annual Meetings in San Antonio (Cuadra, Kimball, Boote, Suyker, & Pickering, 2019). The DSSAT model was described as using "FAO-56" for ET estimation, and the presenter was asked by an audience member where they found or developed their crop coefficients for the method:

Audience member: "You say FAO-56. What are you using for your inflection points for the planting dates and growth phase?"

Presenter: "Inflection point?"

AM: "Yeah, for your trapezoid for your crop coefficients."

P: "See, we don't use those. That's the difference. Kendall DeJonge uses that kind of an input of the engineered coefficients. What creates [what we do] is that we have an extinction coefficient for energy, which is 0.5 on leaf area index, and that partitions the energy to the foliage for potential T[ranspiration]. The rest of it falls to the soil, and that depends on the soil water status and heat capacitance. So, there is no inflection point to go from January 1. It is self-driven."

AM: "I'm talking about the FAO-56 part of it, not your energy…"

P: "Even there we don't, OK. We don't. We still use the leaf area index to do the partitioning to the soil…."

The audience member was clearly an ET scientist who recognized and understood the FAO-56 crop coefficient concept. However, the presenter of the modeling study responded with comments mostly unrelated to FAO-56. Furthermore, the comments incorrectly suggested that there are different ways to implement the FAO-56 methodology (which of course violates the purpose of standardized methods) and unnecessarily injected confusion and conflict into a matter where no debate should exist. The standardized ET methods simply provide a common ET language and method for benchmarking ET estimates. Many researchers need new awareness to appreciate the value of these methods and how they can be applied for model evaluation and improvement.

As a third example, a recent Agricultural Model Intercomparison Project (AgMIP) study compared 29 models for simulations of maize production and ET, using 8 yr of data from an eddy covariance station in Ames, IA (Kimball et al., 2019). This massive project provided considerable insight on the variability of ET outputs among agroecosystem models and the bias issues arising from different modelers working with the same dataset. The effort will undoubtedly serve as a distinguished contribution for the modeling community. Based on supplementary information provided by Kimball et al. (2019), we estimate that 8 of 29 maize models (28%) used reference ET (7 used the standardized ASCE [2005] method, and 1 used the Hargreaves [1975] method) with an FAO-56 crop coefficient approach; 9 of 29 models (31%) used a Priestley-Taylor potential ET approach, which has no standardized formulation; 4 of 29 models (14%) were described as using FAO-56 Penman–Monteith as potential ET with energy extinction and/or without a description of the associated crop coefficient methodology; 1 of 29 models (3%) were described as using Penman–Monteith with simulated resistance (we assume this to be the Penman–Monteith combination equation); 3 of 29 models (10%) used an energy balance ET method; and 4 of 29 models (14%) did not provide enough description to deduce the ET methodology. Thus, while it is difficult to be certain without fully evaluating model code, we estimate that of the 29 models evaluated, 7 fully incorporated an ET methodology based on standardized reference ET (ASCE, 2005) and FAO-56 crop coefficients (Allen et al., 1998), whereas 4 misapplied or misrepresented reference ET approaches as potential ET approaches. As Kimball et al. (2019) showed in a section titled "Consideration of potential ETp simulation," the models computed extremely diverse estimates of potential ET. A likely reason is that potential ET is a nonstandardized concept with loose interpretations, which has led modelers down diverse paths in effort to estimate it. Kimball et al. (2019) also included figures of observed and simulated daily ET_c that have considerable temporal scatter due to daily environmental variability, making the ET behavior among models impossible to interpret. By evaluating model ET behavior using the paradigm for crop coefficients ($K_c = ET_c/ET_{ref}$), differences in ET time-series behavior among models, including physically unrealistic behavior, could have been more readily understood. Fortunately, Kimball and colleagues (2019) have agreed to share their simulation results for the purposes of evaluating the daily ET_c through the lens of the crop coefficient as described by standardized ET procedures, an effort we plan to undertake in the next year.

In future AgMIP ET studies, the use of standardized reference ET methods with appropriate crop coefficients should serve as the benchmark for comparison and the baseline for performance of the various ET approaches among models, where (a) modeling methods that perform more poorly than standardized methods are identified and improved either by fixing coding errors or by simply adopting the standardized ET methods as a better option and (b) modeling methods that perform better than the standardized methods are used to identify algorithm characteristics that offer new insights to ET estimation, leading perhaps to updates of the standardized ET methods themselves. While ET measurements provide the ultimate test of ET algorithm performance, the methodology embodied in ASCE (2005) and Allen et al. (1998) offer a simple, well-documented, and standardized ET algorithm that has been field-tested globally for numerous crops. As such, it should remain the current benchmark algorithm and future springboard for modelers and applied ET practitioners to collectively improve ET estimation and simulation techniques.

4 | CONCLUSION

As researchers who routinely conduct both applied field studies under irrigation management and simulation studies with agroecosystem models, we recognize a severe disconnection in ET communication between applied ET practitioners and agroecosystem modelers. Proper use of standardized ET terminology and methodology is encouraged in all ET applications. We hope the present article and our future efforts will lead not only to better understanding of standardized ET methods among agroecosystem modelers but also to insights on model performance and model improvement options by benchmarking ET simulations using standardized reference ET and crop coefficient methods.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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