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REVIEW

Crop coefficients of natural wetlands and riparian vegetation to compute ecosystem evapotranspiration and the water balance

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Abstract

Wetlands, namely the riparian ones, play a major role in landscape and water resources functionalities and provide enormous opportunities for ecosystems services. However, their area at globe scale is continuously decreasing due to appropriation by the riverain communities or by allocation of water resources to other uses, namely irrigation, in prejudice of natural wetlands. Due to the high competition for water, namely for agricultural irrigation, the calculation of the vegetation evapotranspiration (ET_c), i.e. the consumptive water use of the wetland ecosystems, is mandatory for determining water supply–demand balance at various scales. Providing for the basin and local levels the reason for this review study on ET_c to be presented in an irrigation focused Journal. The review also aims to make available adequate K_c values relative to these ecosystems in an ongoing update of FAO guidelines on evapotranspiration. The review on ET_c of natural wetlands focused on its computation adopting the classical FAO method, thus the product of the FAO-PM grass reference ET_o by the vegetation specific K_c, i.e., $ET_c = K_c\ ET_o$. This approach is not only the most common in agriculture but is also well used in natural wetlands studies, with K_c values fully related with vegetation ecosystems characteristics. A distinction was made between riparian and non-riparian wetland ecosystems due to differences between main types of water sources and main vegetation types. The K_c values are tabulated through grouping wetlands according to the climate since the variability of K_c with vegetation, soil, and water availability would require data not commonly available from the selected studies. Tabulated values appear to be coherent and appropriate to support field estimation of K_c and ET_c for use in wetlands water balance when not measured but weather data may be available to compute the grass reference ET_o. ET_c and the water balance could then be estimated since they are definitely required to further characterization and monitoring of wetlands, defining measures for their protection, and assessing ecosystems' services.

Abbreviations

ASCE-PM-ET_r	Alfalfa reference ETr calculated using an extension of the FAO56 Penman–Monteith equation
ASTER-VI	Vegetation index from ASTER satellite
Avg.	Average
B-C	Blaney–Criddle equation
BREB	Bowen ratio energy balance
Capacit.	Capacitance sensors
DL	Drainage lysimeters
EB	Energy balance
EC	Eddy covariance
EVI	Enhanced Vegetation Index
FAO	Food and Agriculture Organization
FAO56	Food and Agriculture Organization Irrigation and Drainage Paper 56 (1998)
FAO-PM-ET_o	FAO56 Penman–Monteith standardized grass reference ETo equation
FDR	Frequency domain reflectometry
FLUXNET	Global network of micrometeorological flux measurement sites
gravim.	Gravimetric method
Grow-seas	Growing season
GVMI	Global Vegetation Moisture Index
GW	Groundwater
GW Lys.	Water table lysimeter
HS	Hargreaves–Samani equation
HWB	Field or catchment hydrologic water balance
LAI	Leaf area index
Makk	Makkink equation

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Med	Mediterranean
METRIC	Energy balance model for mapping evapotranspiration with internalized calibration
ML	Mini or micro lysimeters
MODIS	Moderate resolution imaging spectroradiometer
NDVI	Normalized Difference Vegetation Index
NOAA-AVHRR	National Oceanic Atmospheric Administration-Advanced Very High Resolution Radiometer
Non-grow seas	Non-growing season
Perm	Permanent river flow regime
PM-eq.	Penman–Monteith combination equation
PT	Priestley–Taylor equation
RS	Remote sensing
RSVI	RS vegetation indices
SEB	Surface energy balance
SEBAL	Surface energy balance algorithm for land model
SEBS	Surface energy balance system model
SF	Sap flow
SR	Surface renewal
Ssflow bed	Sub-surface flow beds
S-SEBI	Simplified surface energy balance index
SSS-ET	Single-satellite-scene method
SW	Double source method of Shuttleworth and Wallace
SWB	Soil water balance
SWC	Soil water content
Temp.	Temporary river flow regime
TDR	Time domain reflectrometer
TSM	Two source model
Trop	Tropical climate
VI	Vegetation index
VVR	Vegetation vitality ratio
Win.	Winter
WL	Weighing lysimeter
WTL	Water table lysimeter

Introduction

The importance of wetlands in influencing water resources, giving relevance to biodiversity and ecosystems services, and in terms of climate change has been widely recognized (Mitsch and Gosselink 2015; Mitsch et al. 2015). Nevertheless, worldwide, the loss of every type of wetlands is continuing (Dixon et al. 2016; Hu et al. 2017). Wetlands are ecosystems of high ecological value and the most biologically rich on the planet (Hauenstein et al. 2014). Each wetland differs due to variations in soils, landscape, climate, water regime and chemistry, vegetation, and human disturbance. This variability of characteristics is well evident through the performed review, resulting that vegetation and ecosystem evapotranspiration varies enormously with those characteristics.

Under the Ramsar Convention (UNESCO 1994) wetlands are areas of marsh, fen, peatland or water presence, whether natural or artificial, permanent or temporary, static or flowing, fresh, brackish or salty, including areas of marine water where its depth at low tide does not exceed six metres. Various classifications of wetlands are in use (EPA 2001; Hu et al. 2017; Ilhardt et al. 2000; Mitsch and Gosselink 2015; Zaimes et al. 2007). Because of their high conservation value, many habitats found in wetlands have been included in the European Habitat Directive (92/43/EEC) (Council Directive 1992), while many of them have been denominated as Nature Reserves, or are Parks, Special Conservation Areas, or other national protected areas. Where river mouths meet the sea, occur unique wetland complexes such as marine and coastal wetlands. The vegetation in these areas ranges from riparian habitats, which differ little from habitats associated with the river upstream, to salt marshes that have a distribution limited to tidally influenced areas with high water salinity. The processes that drive the distribution and dynamics of plant communities in river estuary wetland complexes are also varied, ranging from fluvial-dominated processes, such as flooding and channel migration, to marine processes such as tidally driven water-level fluctuations (Shafroth et al. 2020). Few species can develop and reproduce with repeated exposure to sea water, the halophytes. The latter play an increasingly important role as models for understanding the salt tolerance of plants, or as genetic resources that contribute towards the improvement of salt tolerance in some crops, or for the re-vegetation of saline lands, and as 'niche crops' in landscapes with saline soils (Flowers and Colmer 2015). These coastal systems are among the most vulnerable and threatened habitats on a global scale (Sarika and Zikos 2020).

In inland wetlands, aquatic vegetation typically grows as monospecific patches within streams with patterning caused by self-organization processes. The presence of submerged plants in ponds depends on the season and the water level. The larger aquatic plants that grow in wetlands are the macrophytes, which use solar energy to produce organic matter, which subsequently provides the energy source for heterotrophs (animals, bacteria and fungi). The water and nutrient supply in wetlands make that the primary productivity of ecosystems dominated by wetland plants are among the highest in the world (Adame et al. 2017; Hirota et al. 2007; Miller and Fujii 2010). A high heterotrophic activity is usually associated that creates a high capacity to decompose and transform organic matters and other substances. Macrophytes may be classified as:

i. Emergent: These are the dominating life form in wetlands. Examples include the common reed, palmiet, sawgrass, cattails, bulrushes, watergrass, which often form the border of the wetland or the transition to the upland.
ii. Floating-leaved: These includes species that are rooted in the substrate, e.g. waterlilies, and species that float freely on the surface of the water, e.g. water hyacinth. The freely floating species are highly diverse in form and habit.
iii. Submerged: These have their photosynthetic tissue entirely submerged while the flowers are usually exposed to the atmosphere.

The many functions of wetlands include contributing to the life cycle of plants and animals, by providing habitat, food, nesting sites and shelter for many wildlife species (Nayak and Bhushan 2022). They also moderate climate changes, act as CO_2 sinks, dampen the effect of waves and store floodwaters, retain sediment, and reduce sedimentation and pollution. They are important in the production of food and fodder for domestic and wild animals, and are a source of raw materials for handicrafts (Xu et al. 2020). These animals include alligators, cicadas, manatees, caimans, bullfrogs, beetles, crustaceans, and beavers. Each of these creatures has adapted to life in the wetland environment and plays an important role in keeping the health of the ecosystem. Animals include very rare birds, e.g., the Madagascar pochard (*Aythya innotata*), whose estimated population is less than 150, as analysed by Rose (2021) for birds.

The riparian wetland zone is usually defined as part of the landscape that borders a body of water. These water bodies can be natural, such as streams, rivers and lakes, or man-made, such as ditches, canals, ponds and dams (Zaimes et al. 2007). The active riparian zone refers to a saturated/unsaturated region that is hydrographically connected to the watercourse and directly influences the flow (Sarwar et al. 2022). Verry et al. (2004) proposed and discussed the definition of riparian ecotone as an interaction space comprising terrestrial and aquatic ecosystems. Riparian ecosystems include the physical environment and biological communities that lie at the boundary between freshwater and terrestrial systems. The riparian zone consists of a bank at the channel edge and various types of landforms adjacent to the bank, formed mainly by colluvium deposits in mountainous regions and alluvial deposits in other contexts, with a larger valley floor and a visible floodplain (Dufour et al. 2019). Riparian wetlands can be associated with perennial, intermittent and ephemeral rivers. Perennial streams have in-channel flows all year round and have substantial groundwater flows. Stream flows can vary widely from year to year and may even dry up during severe droughts, but the groundwater table is always near the surface. Perennial streams are found in both humid and arid regions (Zaimes et al. 2007). When the streams are intermittent or ephemeral, they become under a torrential regime, trees may disappear, and shrubby vegetation grows on the banks. Zaimes et al. (2007) referred that intermittent streams/riffs are also linked to the groundwater, which is located immediately below the stream bed, even if there is no flow. These streams are usual in arid and semi-arid climates, with the oasis belonging to this group of riparian vegetation. The riparian ecosystems are the most dynamic, productive, and vulnerable ecosystems in drylands, and they are centres of human life and economic development in arid and semi-arid regions (Chen et al. 2023); thus, because water is the scarcest and most constrained resource in drylands, increasing water demand could potentially threaten regional water security. The Ejina oasis, in NW China, located at the interface between Alasan highlands and desert is an example (Hou et al. 2010). In such arid regions, water resources become the key driving factor of ecological environment evolution, and it is the main constrain to the maintenance of ecosystems. The riparian zones are transition zones and have characteristics of both aquatic and upland terrestrial ecosystems (Zeng et al. 2020). This is reflected in the presence of a greater number and diversity of species (Zaimes et al. 2007). The characterization of wetlands ecosystems needs to include the evapotranspiration (ET_c), i.e., the consumptive water use of the ecosystem, and the water balance, which determine the dynamics of the relationship between supply and demand. Their knowledge allows to better define how to protect the system and assessing the ecosystem services.

Riparian wetland ecosystems are recognised as highly diverse and containing specialised ecological communities as well as providers of multiple ecosystem services (Kaletová et al. 2019; Xu et al. 2019; Mandžukovski et al. 2021). The most important functions of riparian vegetation (Zaimes et al. 2007; Dickard et al. 2015; Zeng et al. 2020) are: to enhance habitat for terrestrial and aquatic fauna; to retain sediments and nutrients resulting from runoff or from flooding; to mitigate the pollution resulting from agriculture through detention, buffering and processing; to stabilise and to strengthen the stream banks; to store water and recharge the underground aquifers; to reduce flood runoff. The functional riparian zones enhance the water quality and carbon sequestration (Mandžukovski et al. 2021). Well-functioning riparian zones improve regional biodiversity, and the resilience of landscapes to climate change and related hydro-climate impacts (Mandžukovski et al. 2021). Better knowing these functions require knowledge of the dynamics of ET_c and of the wetland water balance. Biological importance is also linked to habitat availability and the role of wildlife corridor (de la Fuente et al. 2018), and the vegetation's effect on biodiversity. On a social level (Dufour et al. 2019), riparian vegetation contributes to the landscape identity to which it is a part; for example, providing a contribution to creative services (recreation, inspiration, etc.). Climate has a strong influence on the function and structure of the riparian zones through temperature, precipitation, evapotranspiration, and runoff (Verones et al. 2013), which determine their water balance and recognizing the role of flood events as influencing the species composition.

The agriculture zones are usually located on river floodplains, and use water diverted from the river to irrigate crops. Agriculture is the primary source of income for the surrounding communities; thus resource managers need accurate estimates of water requirements of both crops and riparian vegetation and allocate water. Water governance must have that knowledge and the voice of the riverain communities; otherwise, wetlands decline as analysed by Nouri et al. (2023) for Iran where water is increasingly used for irrigation in arid zones. The major direct change in converting a riparian area to agricultural area is the change in vegetation and consequently in ET_c, i.e., the consumptive water use, and area water balance or alteration of the supply–demand dynamics. Various studies have identified negative (Galbraith et al. 2005) and positive (Sueltenfuss et al. 2013) interactions between wetlands and irrigation**.**

The increase in cropped area can lead to higher peak flows and subsequent flooding downstream. Increased flows in the stream channel in turn lead to greater stream incision and stream bank erosion. The base flow decreases because water flows out of the watershed very fast. These changes alter the local hydrologic cycle and have converted many perennial streams into intermittent or ephemeral streams (Zaimes et al. 2007). For example, in the middle reaches of the Tarim River (China), cropland expanded with increasing population and demand for grain. As a result, increasing amounts of runoff from the upper reaches were captured and used to irrigate crops. This has resulted in less runoff entering the lower reaches of the river, causing there a variety of problems such as river-flow interruptions, drying up of terminal lakes, shrinkage of natural vegetation areas, land desertification, intensified sandstorms, soil salinization, and declining water quality (Mamat et al. 2018). This example also evidences the need for knowing ET_c and the water balance if the protection of the riparian vegetation is intended, namely to balance the potentially negative impacts of agriculture. Riparian zones may play a crucial role in the water balance of a catchment and in the hydrological process (Yu et al. 2016; Sarwar et al. 2022).

To maintain the biodiversity of riparian and wetland vegetation around the world, it is important to recognize that these zones are vital areas of interaction between land and water bodies and are often degraded by various pressures such intensive agriculture and river engineering works (Urbanič et al. 2022). The most severe and common human impacts are due to land-use conversion to agriculture, streamflow regulation, nutrient enrichment, and climate change. Adopting an integrated socio-economic and environmental dynamic perspective will ensure the sustainable management of riparian and wetlands. In light of climate change, it is critically important to conserve and/or restore the ecological integrity of these areas. Plant species in all regions are adapted to multiple abiotic stressors, including dynamic flooding and sediment regimes and seasonal water shortage. Current knowledge gaps and subjects for future research include cumulative impacts to small, ephemeral streams and large, regulated rivers, as well as understudied ecosystems in North Africa, the western Mediterranean basin, and Chile (Stella et al. 2013). Research on vegetation evapotranspiration is helpful in understanding the water balance of riparian forests, especially in the extreme arid regions, and can be used to determine the actual ecological water demand of desert riparian forest and other areas. Thus, research can contribute to the rational use of water resources, protection, and maintenance of the stability of the riparian forest system and wetland vegetation (Hou et al. 2010). An example of native plants reestablishment by controlling invasive saltcedar (*Tamarix* spp.) in riparian areas of the Southwestern USA by inducing its transpiration reduction is reported by Solis et al. (2024). Updated knowledge on management of riparian wetlands is provided by Johnson et al. (2018) and Carothers et al. (2020).

In order to study, monitor, design and implement protection and conservation measures, it is necessary to determine the water balance of wetland systems and therefore to have a reliable and simple methodology for computing evapotranspiration. The referred FAO approach – $ET_c = K_c\ ET_o$ – is already in use in agriculture and in multiple natural on-site studies. Its simplicity and the fact that K_c represents the different responses of the vegetation and varies with the location, particularly with the wetness or dryness of the climate and the soil and vegetation. When recognizing the seasonal ET_c characteristics of the ecosystems, the characteristics of climate and the typical vegetation, it is possible to transfer in space the K_c values and provide for a simple estimation of ET_c of the vegetation in a different location. This procedure is in use after long time, reason why updates for tree and grass crops were recently published (Pereira et al. 2023a, b), so preceding this paper. Naturally, the precision of estimators may not be very high because wetlands are complex systems and it depends on the knowledge and experience of researchers, but it may be quite precise in terms of experimental approach. As a starting point for the application of this approach, there is the need for a wide estimation of the K_c values.

The main objective of the study therefore consists of the review collection of available K_c values for a variety of wetlands and riparian ecosystems, which is resolved through the tabulation of K_c and the related basic characteristics of respective locations. An essential objective is the use of tabulated K_c with ET_o computed from local observations to easily and accurately estimate ET_c, so to calculate the areal water balance and the supply demand balance focused on the protection of wetlands and riparian zones and on the assessment of their ecosystem services. Another objective consists of using the tabulated K_c to select a set of wetlands and riparian ecosystems to update the wetlands K_c section in the revised version of FAO56 guidelines (Allen et al. 1998). A further objective is to make available a tabulated collection of K_c values that can be used to check field results in the research practice. An additional objective is to make available such tabulated K_c values for use in water resources studies where water balance and demand–supply studies are required.

Material and methods

Evapotranspiration

The current review based upon collecting published evapotranspiration studies that reported on crop coefficients (K_c) for natural wetlands and riparian vegetation ecosystems, providing for easy calculating ecosystem (ET_c) with the FAO procedure (FAO56, Allen et al. 1998). As introduced earlier, this method uses the product of the grass reference ET_o, defined with the equation FAO-PM ET_o (FAO56, Allen et al. 1998), by a crop (vegetation) coefficient K_c that represents the differences between the considered crop (vegetation) and the grass reference crop in terms of transpiration by the canopies and soil evaporation. Thus, K_c is defined by the ratio ET_c/ET_o. The review was performed through the widest possible internet search focused upon papers reporting on K_c obtained from field measurements of actual ET_c of wetlands and riparian vegetation ($ET_{c\ act}$).

The daily rate of evapotranspiration ET [mm d^{-1}] can be computed with the Penman–Monteith combination equation (PM, Monteith 1965):

$$ET = \frac{1}{\lambda} \frac{\Delta (R_n - G) + \rho c_p (e_s - e_a)/r_a}{\Delta + \gamma (1 + r_s/r_a)} \quad (1)$$

where λ is the latent heat of vaporization [kg m^{-3}], R_n-G is the net balance of energy available at the surface [MJ m^{-2} d^{-1}] computed as the difference between the net radiation R_n and the soil heat flux G, (e_s—e_a), difference between the vapor pressure of the air at saturation e_s and at actual conditions e_a, represents the vapor pressure deficit (VPD) of air at the reference (weather measurement) height [kPa], represents mean air density [kg m^{-3}], c_p represents specific heat of air at constant pressure [kJ kg^{-1} °C^{-1}], is the slope of the saturation vapor pressure–temperature relationship at mean air temperature [kPa °C^{-1}], is the psychometric constant [kPa °C^{-1}], r_s is the (bulk) surface resistance [s m^{-1}], and r_a is the aerodynamic resistance [s m^{-1}]. Equation 1 is used to compute $ET_{c\ act}$ from field observations; it would be often used in practice if the resistances r_s and r_a of the considered vegetation would be easily known. Several studies report that these parameters have to be calibrated using field measurements of $ET_{c\ act}$ with eddy covariance (EC) systems, or the Bowen ratio energy balance (BREB) instrumentation, as referred to in the tables hereafter. However, r_s and r_a cannot but exceptionally be standardized, resulting that the PM Eq. (1) is not commonly used predictively.

The PM Eq. (1) was used to develop the FAO-PM ET_o equation for the grass reference crop, which was standardized as a hypothetical crop with an assumed height of 0.12 m having a fixed daily average surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling an extensive surface of green grass of uniform height, actively growing, free of diseases and adequately watered. This definition allows the parameterization of r_s and r_a and, replacing them in Eq. 1, in the FAO-PM ET_o equation, thus (Allen et al. 1998, 2006):

$$ET_o = \frac{0.408\Delta (R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + C_d u_2)} \quad (2)$$

where, in addition to the variables defined for Eq. (1), T is mean daily air temperature [°C] and u_2 is wind speed [m s^{-1}], both measured at 2 m height. For daily computations, the surface resistance is assumed $r_s = 70$ s m^{-1}, resulting $C_n = 900$ and $C_d = 0.34$. When using an hourly time-step computation $C_n = 37$, while $C_d = 0.24$ during daytime ($R_n > 0$), assuming $r_s = 50$ s m^{-1}, and $C_d = 0.96$ during nighttime because $r_s = 200$ s m^{-1}.

The American Society of Civil Engineers (ASCE) adopted both the grass and alfalfa reference, respectively ASCE-PM ET_o and ASCE-PM ET_r, with alfalfa having a standardized height of 50 cm, then having different values for C_n and C_d (Eq. 2). Due to the lower r_s and higher r_a of alfalfa, $ET_r \approx 1.15\ ET_o$. This ratio is adopted in the current study.

The computation of the PM-ET_o equation parameters should follow the procedures described by Allen et al. (1998) but, in many parts of the world, data on some weather variables are often missing, or are of low or questionable quality, namely solar radiation, air humidity and wind speed. The missing variables can then be estimated using the procedures proposed by Paredes et al. (2020, 2021) and in the new coming FAO56 revised, namely referring to the Hargreaves equation (HS), or to the use of reanalysis weather data or stationary satellite grided data (Allen et al. 2021; Paredes et al. 2021).

Crop coefficients

Assuming the FAO approach to compute ET_c

$$ET_c = K_c\,ET_o \tag{3}$$

it is important to recall that, being solely computed with weather variables, not observed, ET_o represents the climatic demand on evaporation. K_c represents an integration of the effects of three primary characteristics that distinguish the crop or vegetation from the reference: the crop height, h, and the aerodynamic resistance; the crop-soil surface resistance, r_s and the albedo, α, of the crop-soil surface. Thus, K_c is little influenced by the climate and standard K_c values for the same crop or type of vegetation can be transferred between locations and climates.

In the current study, a time-averaged K_c is adopted since it includes multi-day effects of evaporation and transpiration. For wetlands and riparian vegetation these effects are generally combined and there is no need to separate evaporation and transpiration. The changes in K_c over the growing season are represented by the crop coefficient curve (Fig. 1), which relates to changes in the vegetation and ground cover through the crop season that affect the ratio ET_c/ET_o at the four growth stages considered: initial, development, mid-season and late season as per Fig. 1.

The K_c generally increases from an initial value, $K_{c\ ini}$, until reaching a maximum, $K_{c\ mid}$, at the mid-season period, the time of maximum or near maximum plant development (Fig. 1). During the late season period, vegetation progressively senesces or becomes dormant, and leaves senesce and eventually dry out and fall, the K_c generally decreases until it reaches a lower value, $K_{c\ end}$, at the end of the plant season. The late season ends quickly, sometimes abruptly, when frost affects the vegetation and induces their dormancy, i.e., the length of the late-season period may be relatively short for vegetation killed by frost. The length of plant stages is vegetation-specific and change duration with weather conditions, mainly air temperature. The lengths of the initial and development periods may be relatively short for deciduous trees and shrubs that develop new leaves in the spring at relatively fast rates. The value for $K_{c\ end}$ should reflect the canopy condition of the vegetation immediately before plant death.

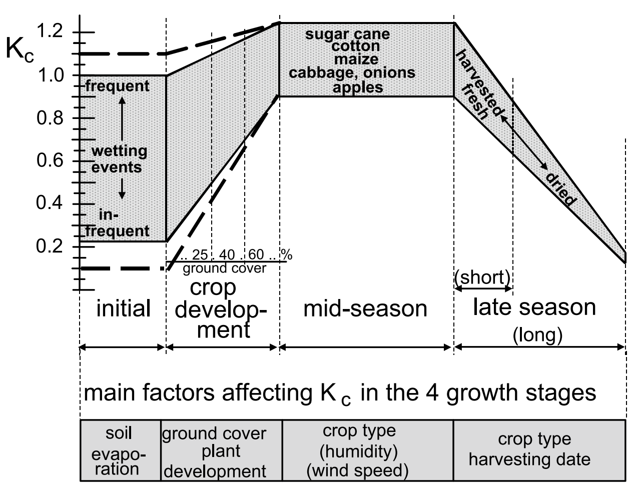

Fig. 1 Typical crop coefficient curve referring to four growth stages and the main factors affecting their duration and variation with the type of vegetation and crop management (source: Allen et al. 1998)

The four crop growth periods in Fig. 1 are: (i) *Initial*: for annuals, the duration of this phase is from planting date or, for perennials, from the "greenup" date when initiation of new leaves occurs, to approximately 10% ground cover; (ii) *Development*: from 10% ground cover to effective full cover; (iii) *Mid-Season*: from effective cover to start of maturity or senescence, often indicated by the beginning of the ageing, yellowing or senescence of leaves or leaf drop; (iv) *Late Season*: from start of maturity or senescence to full senescence or dormancy. To draw the K_c curve three K_c values have to be known—$K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ -, which need to be connected by straight line segments through each of the four growth stage periods. This procedure applies to all types of vegetation but with different durations of crop stages (Fig. 2), which must be identified by the users.

Annual crops tend to have longer initial, development and late-season durations than perennials. Among the latter, grasses, reeds and deciduous trees and shrubs may have short initial and development stages depending on climate. Differently, evergreen trees and shrubs may do not have a distinction among phases, depending upon climate. This variability is evident in Tables presented in "Crop coefficients for wetlands" and "Crop coefficients for wetland riparian ecosystems" sections for both wetland and riparian ecosystems. Vegetation K_c varies throughout the growth season with variations in physiologic plant response to the atmosphere demand, but K_c is time averaged for the initial and mid-season stages referred above, thus are then considered not changing. For research purposes, it may be of interest to consider it variable, e.g., depending upon the indices of vegetation (VI) as defined in remote sensing. Glenn et al. (2011) proposed the use of K_c estimated as a function of the variable parameter EVI. However, considering the variability of mixed vegetation, the time averaged K_c is adequate for most uses. In remote sensing, K_c values are often replaced by the index EToF, fraction of ET_o, which varies with time (Glenn et al. 2011).

Field research methods in wetlands literature included: (i) the soil water balance (SWB) based on observations of the soil water content using soil sampling or various types of sensors; (ii) the catchment hydrologic water balance

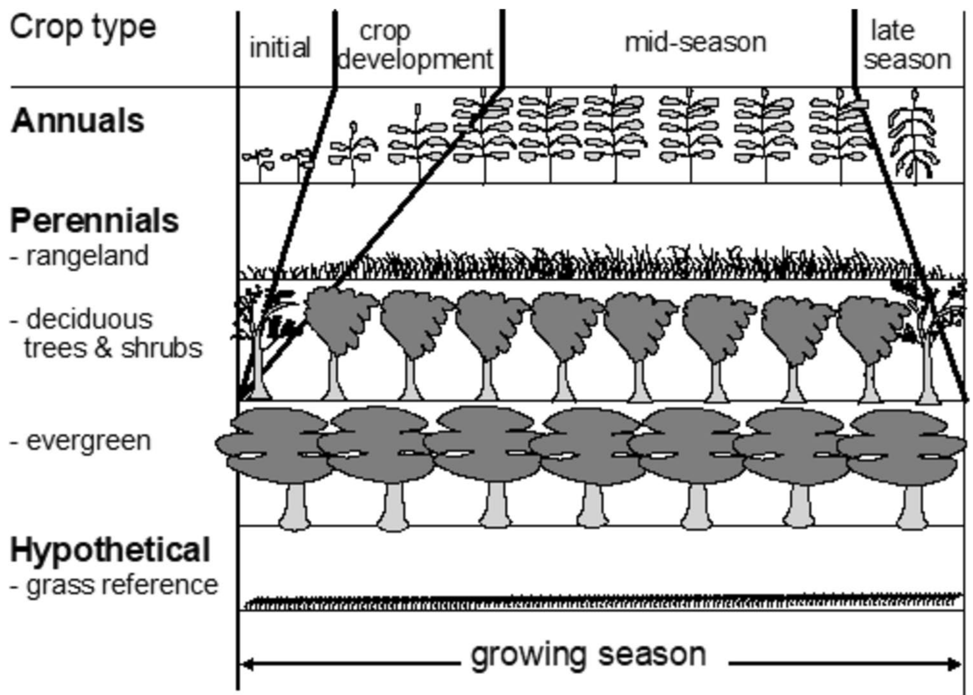

Fig. 2 Crop growth stages for different types of vegetation, annuals and perennials, deciduous and evergreen, compared with the grass reference crop (source: Allen et al. 1998)

(HWB); (iii) the Bowen ratio energy balance (BREB); (iv) the eddy covariance system (EC); (v) weighing, drainage and water table lysimeters (WL, DL and WTL); (vi) mini or micro lysimeters (ML) to assess soil evaporation; and (vii) diverse but consistent empirical methods such as testing different K_c values against observed yields. Most field methods are analyzed for accuracy by Allen et al. (2011).

The methods used to compute and assess $ET_{c\ act}$, in addition to the FAO56 method (Allen et al. 1998), included the Penman method (Doorenbos and Pruitt 1977), the Penman–Monteith combination equation (Monteith 1965, PM), the Priestley and Taylor equation (1972, PT), and the double source method of Shuttleworth and Wallace (1985, SW). The PM, the PT and the SW equations require specific field methods. Several studies were performed with support of models with proper calibration. The most used software models comprise SIMDualKc (Rosa et al. 2012) and HYDRUS (Šimůnek et al. 2016). In addition, remote sensing (RS) was largely used, mainly in the last decade, and surface energy balance models (SEB), e.g. METRIC, SEBAL and SEBS (Allen et al. 2007), and RS vegetation indices (RSVI, Pôças et al. 2020), were used. A list of symbols, acronyms and abbreviations is included at end of the article in Abbreviation section.

Selection and use of bibliography data

The search was performed in Science Direct and through the pages of various journals, as well as using bibliography listed in selected articles. English, Spanish, Portuguese, French, Italian and German languages were considered. The search keywords, in addition to evapotranspiration, crop coefficients, wetlands and riparian vegetation, included designations of common plants of these ecosystems. Only full articles were reviewed. Papers were selected when they evidenced good/satisfactory quality of field research, regardless of the journals in which they were published, and where both ET_o and ET_c were appropriately calculated/estimated. The approach described was adopted in previous K_c reviews by Pereira et al. (2023a, b). Generally, selected papers required:

1. The use of the grass reference FAO-PM-ET_o equation.
2. That the conversion ratio from the used ET_o or ET_r equation to the FAO-PM-ET_o, was known.; a conversion factor of 1.15 was used when the ASCE-PM ET_r equation for alfalfa (Eq. 2) or the Penman equation were adopted.
3. The field methods were well described and should refer to consistent methodologies that provide for computing $ET_{c\ act}$ accurately as proposed by Allen et al. (2011).
4. The K_c values should have been derived from adequate field research and well discussed.
5. Tthe K_c values were provided in Tables, graphics or in the text, preferably with a specific discussion; for a

Table 1 Field observed actual crop coefficients for wetlands in freezing winter climates and high elevation sites

Identification	Reference	Dominant species	Method for estimating ET_o and $ET_{c\ act}$	Actual crop coefficient derived from field observations				
				Conditions	$K_{c\ avg}$	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
High elevation meadow in Qilian Mountains, China	Yang et al. (2017)	*Kobresia capillifolia, Carex moorcroftii*	FAO56-ET_o	Whole year		0.10	1.00	0.20
				Unfrozen seas		0.10	1.15	0.50
				Froze period		0.15		0.25
High elevation swamp meadow, Qinghai, Yangtse basin, China	Li and Wang (2015)	*Stipa aliena, Kobresia tibetica, Festuca* spp.*, Carex atrofusca*	FAO56-ET_o EC	Apr–Oct	0.55	0.20	0.85	0.20
Humid alpine meadow Haibei. NE Qinghai-Tibetan Plateau, China	Dai et al. (2021)	*Kobresia* spp. Perennial sedge and graminoid	FAO56-ET_o WL	May–Sep	1.01	0.70	1.19	1.12
				Oct–Apr	0.45			
Swamp meadow in Qinghai–Tibet Plateau, China	Guo et al. (2022)	*Kobresia littledalei, Carex moorcroftii*	FAO56-ET_o EC & SWB-HydraProbe	Jun–Oct, modified K_c		1.14	1.14	1.05
Wetland NW of Upper Klammath Lake, Oregon, USA	Stannard et al. (2013)	*Scirpus lacustris*	ASCE-ET_o METRIC	Grow-seas	0.84	0.66	1.05	0.45
				Non-grow-seas	0.68			
		S. lacustris, Typha spp.*, Nuphar polysepala*		Grow-seas	0.80	0.64	0.99	0.38
				Non-grow-seas	0.76			
Wetlands, Minnesota River, Minnesota, USA	Baeumler et al. (2019)	*Carex* spp.*, Calamagrostis* spp.*, Typha* spp.	ASCE-ET_r METRIC		1.00	0.85	1.15	0.75
Wetlands in northern New York State, USA	Hwang et al. (2020)	*Typha* spp.*, Schoenoplectus acutus*	FAO56-ET_o SEB & BREB			0.85 0.84	1.23 1.26	
		Typha spp.				0.97	1.21	
High elevation Huagrauma Andean paramo, Ecuador	Buytaert et al. (2006)	n/r	FAO56-ET_o Catchment WB	Grass with dead leaves	0.42		0.42	
High elevation Andean paramos of Zhurucay, Ecuador	Carrillo-Rojas et al. (2019)	*Calamagrostis intermedia, Festuca* spp.*, Azorella* spp.*, Gentiana* spp.*, Polylepis* spp.*, Buddleia* spp.	FAO56-ET_o EC	Wet conditions	0.93		0.93	
				Less wet conditions	0.87		0.87	

Symbols, abbreviations and acronyms are given in Abbreviation section

few cases, when only $ET_{c\ act}$ and ET_o were provided, K_c (average) values were computed. Otherwise, data were not considered.

6. The description of the studied wetland or riparian vegetation, with identification of main species, should be as complete as possible.
7. The computation methods should be sufficiently descriptive, and models should be calibrated and validated in line with the recommendations by Allen et al. (2011) to understand if the reported methods provided for reliable data. Otherwise, the study was not considered.

Crop coefficients for wetlands

The search on wetlands actual ET ($ET_{c\ act}$) and K_c provided a good number of case studies covering most of the wetland types, many of them recognized by the RAMSAR Convention. However, since not all authors classified the described wetlands, their analysis could not be performed according to a common wetland classification, nor in relation to the dominant vegetation due to its very wide variability. The option was then to group the reported wetland case studies according to the climate since it influences enormously the type of dominant vegetation and its evapotranspiration and K_c values. Related information was summarized in Tables,

Table 2 Field observed actual crop coefficients for wetlands in cold winter climates

Identification	Reference	Dominant species	Method for estimating ET_o and $ET_{c\ act}$	Actual crop coefficient derived from field observations				
				Conditions	$K_{c\ avg}$	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
Teesmouth estuary,Himley & WaltonLake, England	Fermor et al. (2001)	*Phragmites australis*	Modif. PM ET_o Phytometers	Teesmouth stuary		0.89	1.43	0.94
				Himley		0.50	1.20	0.69
				Walton Lake		0.48	0.80	0.76
Common reed atStodmarsh, Kent, UK	Peacock and Hess (2004)	*Ph. australis*	FAO56-ET_o BREB	Dry periods Wet periods	0.53 0.88			
Reed at Stodmarsh,Kent, UK	Peacock and Hess (2004)	*Ph. australis*	FAO56-ET_o BREB	Jul–Aug, wet days	0.97			
				Jul–Aug, sunny days	0.59			
Reed beds inAqualate MereMidlands, UK	Read et al. (2008)	*Ph. australis*	Morecs-PM-ET_o Reed-bed lysimeter	Year		0.30	0.90	0.60
Lake Balaton, Hungary	Anda et al. (2014)	*Ph. australis*	FAO56-ET_o Mod. lysimeter	Cold year		0.50	0.80	0.40
				Normal year	1.23	0.80	1.50	0.90
Fenéka pond, Kis-Balaton Lake,Hungary	Anda et al. (2015)	*Ph. australis* *Typha* spp.	FAO56-ET_o Modified drainage lysimeters	Tally emergent	1.14			
		Carex spp.		Leafy emergent	1.00			
		Salix cinerea, S. alba		Woody shrub	0.85			
		Alnus glutinosa		Woody deciduous	0.75			
		Festuca rupicola		Grassland	1.00			
Wet grasslands atHavelländischesLuch (**HL**) andSpreewald (**SPW**),NE Germany	Dietrich et al. (2021)	Grasses for cutting	FAO56-ET_o EC	**HL**: grow-seas	0.91			
				Non-grow-seas	1.06			
			FAO56-ET_o WT Lysimeter	**SPW**: grow-seas	0.92			
				Non-grow-seas	1.03			
Yellow River Delta, Shandong, China	Jia et al. (2009)	*Suaeda heteroptera*	FAO56-ET_o MODIS, SEBS	Open sky	1.02		1.22	
				Cloudy			0.93	
Yellow River Deltaswamp, Danjiying,Shandong, China	Jia et al. (2009)	*Ph. australis*	FAO56-ET_o MODIS, SEBS	Open sky	1.11			
				Average	1.03			
				Cloudy	0.97			
Panjin wetland, Liaoning, China	Zhou and Zhou (2009)	*Ph. australis*	FAO56-ET_o EC, SW-TDR, Energy balance	Year	0.53			
				Grow–season	0.71	0.20	1.10	0.40
Grass marsh innorthern Taiwan	Yao et al (2017)	*Brachiaria mutica*, *Ph. australis*	FAO56-ET_o EC	Year	0.66			
Reed swamp, Amu-Darya, Lebap Prov. Turkmenistan	Thevs et al. (2014)	*Ph. australis*	FAO56-ET_o Regression with nearby BREB	April–Sep	1.15			

Symbols, abbreviations and acronyms are given in Abbreviation section

which are quite useful for readers to compare among the table-grouped case studies.

The Tables 1, 2, 3, 4 and 5 provide information on the location of the studied sites, the authors, the dominant vegetation species, the methods used for estimating of ET_o and $ET_{c\ act}$, which allow readers to better compare results and to perceive the confidence on their computation, and the actual crop coefficients derived from field observations for the initial stage, the mid-season and the end season, as well as the average value for the vegetation season. When opportune, conditions relative to the estimated K_c are also referred, e.g., the duration of the vegetation cycle. Differently, Table 6 provides summarized information about diverse vegetation species whose data could be duly assigned to them. Plants nomenclature, morphology and ecology in Table 6 are those referred in a flora site where the third author collaborates: http://www.worldfloraonline.org.

Table 1 presents K_c values relative to wetlands located in regions of freezing winter climates but warm summer in high elevation areas, thus where the vegetation season is short, about 6 months. Killing frost is likely to occur there, which could induce end season K_c to fall abruptly

Table 3 Field observed actual crop coefficients for wetlands in temperate climates

Identification	Reference	Dominant species	Method for estimating ET_o and $ET_{c\ act}$	Actual K_c derived from field observations				
				Conditions	$K_{c\ avg}$	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
Cattail in Southern Florida, USA	Allen (1998)	*Typha latifolia*	ASCE ET_r PPM comb. Eq	Large stand		0.60	1.00	0.60
Fort Drum Marsh, Central Florida, USA	Mao et al. (2002)	*Typha latifolia*	FAO56- ET_o DL	Growing season	0.77		0.83	
				Non-grow. Seas			0.64	
		Cladium jamaicense		Growing season	0.98		1.09	
				Non-grow. Seas			0.73	
		Open water		Spring to Fall	0.77		0.80	
				Winter			0.68	
Wetlands in Lake Okeechobee basin, Florida, USA	Min et al. (2010)	*Juncus effusus, Panicum* sp., *Pontederia cordata, Ludwigia repens, Andropogon glomeratus*	FAO56-ET_o Test K_c values	Mixed	0.75	0.53	0.85	0.53
Marsh site near Everglades and Lake Reedy, Florida, USA	Chin (2011)	Marsh site	FAO56- ET_o EC, Pmeq, PT	Winter–Spring Summer–Fall	0.90 1.09			
		Reedy Lake, open water		Winter–Spring Summer–Fall	1.00 1.12			
Subtrop. wetland, Central Florida, USA	Wu and Shukla (2014)	*Typha latifolia* *Cladium mariscus*	FAO56-ET_o EC, Pmeq	Winter			0.87	
				Summer			0.99	
Twitchell island, Sacramento & San Joaquin Delta, USA	Drexler et al. (2008)	*Typha latifolia*	ASCE-ET_o Surf. Renewal	May–Oct	0.95	0.80	1.04	0.90
Intertidal salt marsh, San Francisco Bay, California, USA	Moffett et al. (2010)	*Sporobolus foliosus, Distichlis spicata, Salicornia depressa*	Class A pan PT and PM equations	Overall	1.02			
				Non-flooded	0.98			
				Flooded	1.14			
Wetland in Kern River, S. Joaquin Valley, USA	Howes et al. (2015)	*Schoenoplectus* sp.	ASCE- ET_o METRIC with LandSAT 5	Large stand, Apr–Oct		0.90	1.14	1.15
Temperate salt marshes, Newcastle, Australia	Hughes et al. (2001)	*Sarcocornia quinqueflora, Sporobolus virginicus, Triglochin striata*	FAO56-ET_o EC and PM eq	Salt marshes, Aug–Oct	0.85			
Ortülüakar marsh, Sultan Marshes, Central Turkey	Dadaser-Celik et al. (2006)	*Phragmites australis*	Pan class A SWB & water level sim	Standing water	1.17	1.10	1.30	1.10
				Moist soil	0.95	0.80	1.26	0.80
Coastal wetlands, Liangduo estuary, Jiangsu, China	Yuguda et al. (2022)	*Ph. australis,* *Spartina alterniflora*	FAO56-ET_o 12 DL	Apr–Oct Apr–Oct		0.72 0.95	0.97 1.18	0.72 0.80
Common reed in Veneto and Sicily Italy	Borin et al. (2011)	*Ph. australis* (Jun–Sep)	ASCE-ET_o Small tanks	Veneto	0.68	0.47	0.82	n/r
			ASCE-ET_o Ssflow bed	Sicily	0.63	0.23	0.85	n/r

Table 3 (continued)

Identification	Reference	Dominant species	Method for estimating ET_o and $ET_{c\ act}$	Actual K_c derived from field observations				
				Conditions	$K_{c\ avg}$	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
Experimental wetland perennials for biomass energy, Padova, NE Italy	Barco et al. (2018)	*Arctium lappa*	FAO56-ET_o SWB-capacit	Apr–Oct	1.0–1.1			
		Arundo donax			0.8–0.9			
		Carex acutiformis			1.1			
		Carex tiparia			0.9–1.1			
		Glyceria maxima			1.0			
		Helianthus tuberosus			0.5–1.3			
		Iris pseudacorus			1.0			
		Lythrum salicaria			1.0–1.4			
		Miscantheus giganteus			0.9–1.1			
		Symphytum uplandicum			0.8–1.1			

Symbols, abbreviations and acronyms are given in Abbreviation section

after very low temperatures would cause a sudden period of dormancy. In the case of meadows, which are quite common in these regions, $K_{c\ end}$ may be high, close to $K_{c\ mid}$, due that abrupt transition to dormancy, or low if dormancy is not completely abrupt. The first condition likely occurred in the two meadows on the Qinghai–Tibet Plateau (Dai et al. 2021; Guo et al. 2022), while the $K_{c\ end}$ values does reflect a slow entrance in dormancy in case of meadows reported by Yang et al. (2017) and Li and Wang (2015). Other wetlands, with more complex vegetation reported, may have been affected by abrupt high cold in the Fall, but the $K_{c\ end}$ values do not reflect well that condition or are lacking (Baeumler et al. 2019; Hwang et al. 2020). Also likely influenced by freezing winter is the case of high elevation Andean "páramos" of Ecuador, reported by Carrillo-Rojas et al. (2019), which shall have high values of $K_{c\ ini}$ and $K_{c\ end}$ since the average K_c equals $K_{c\ mid}$.

The actual K_c values in the initial stage are extremely varied, likely influenced by the timing of field observations and by the response to the climate. When field research starts early in the season, the $K_{c\ ini}$ value is low; contrarily, it is high when observations start late. However, the initial conditions could not be assessed when reviewing the papers. The case of mountain swamp meadows reported by Li and Wang (2015) and Yang et al. (2017) likely refer to vegetation that responded slowly to the atmosphere demand. Differently, the studies reported by Dai et al. (2021), Guo et al. (2022), Baeumler et al. (2019), Hwang et al. (2020) and Carrillo-Rojas et al. (2019) probably are cases where the initial stage was quite long, ending when evapotranspiration was close to $ET_{c\ mid}$.

The $K_{c\ mid}$ values and the season $K_{c\ avg}$ vary less than the initial and end K_c values because both represent several weeks or month averages. The lowest $K_{c\ mid}$ value refers to a high elevation Andean páramo of Ecuador (Buytaert et al. 2006), likely not used for grazing since it is referred that plant leaves fall and create a mulch that highly reduces ET_c. Its results are not comparable with those reported for another high elevation Andean páramo that has a K_c value that double the former and is used for grazing (Carrillo-Rojas et al. 2019). Generally, meadows and grasslands have relatively high $K_{c\ mid}$ values, from 0.85 to 1.26, and $K_{c\ avg}$ often close to 1.0.

The wetlands in mostly temperate regions having cold winter and a warm summer are described in Table 2. These study cases mostly refer to Europe while those in more stringent climates refer to China and Turkmenistan. Reeds in swamps and marshes are the most common vegetation and have high $K_{c\ mid}$ values, generally higher than 1.00, up to 1.50. This high value of 1.50 reported by Anda et al. (2014) is likely due to local advection contributing to the energy used for evaporation, which probably occurs if patches of high reed are surrounded by low vegetation. Reeds have

Table 4 Field observed actual crop coefficients for wetlands in warm climates

Identification	Reference	Dominant species	Method for estimating ET_o and $ET_{c\ act}$	Actual crop coefficient derived from field observations				
				Conditions	$K_{c\ avg}$	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
Low Colorado River, USA	Jensen (2003)	*Phragmites* spp.	FAO56-ET_o Review, NDVI	*Phragmites* spp.		0.85	1.00	0.85
		Typha spp. *Schoenoplectus* spp		Swamp		0.25	1.20	0.25
Cienega de Santa Clara, Colorado River Delta, Mexico	Glenn et al. (2013)	*Typha domingensis*	FAO56-ET_o SEB and BREB	After fire No fire		0.20 0.20	0.90 0.60	0.25 0.25
Caballo Lake, Rio Grande, New Mexico	Bawazir et al. (2014)	*Distichlis spicata*	ASCE-ET_o EC	Salt marshes		0.17	0.57	0.33
Swamps of the upper Nile, from Mangala to Malakai, Sudan	Mohamed et al. (2004)	*Eichhornia crassipes, Vossia cuspidata, Cyperus papyrus, Phragmites karka, Typha domingensis*	FAO56-ET_o Model SEBAL, NOAA-AVHRR	Neyala		0.20	0.50	0.40
				Malakai		0.30	1.00	0.40
				Sudd		0.60	1.05	0.67
				Juba		0.50	1.00	0.70
Coastal wetland Mfabeni Mire, Maputaland, RSA	Clulow et al. (2012)	*Rhynchospora holoschoenoides, Fimbristylis bivalvis*	FAO56-ET_o Surface renewal	Full year	0.80	0.50	0.95	0.47
Jonkershoek, West. Cape, RSA	Rebelo et al. (2020)	*Prionium serratum*	FAO56-ET_o Modis-SEBAL	Full year	1.06	0.94	1.10	1.00
Wet savanna forest Pantanal, Mato Grosso, Brazil	Sanches et al. (2011)	*Vochysia divergens* forest	FAO56-ET_o Fluxtowers energy balance		0.75			
Florida + California Large and small stands of wetlands vegetation	Howes et al. (2015)	*Typha* spp. & *Schoenoplectus* spp.	FAO56-ET_o Various FAO56 approaches	L. stand Florida California		0.67 0.70	1.10 1.12	0.75 0.75
		Schoenoplectus acutus *Schoenoplectus* spp.		L. stand seasonal		0.70	1.10	0.75
		Typha spp.		Small stand		1.28	1.61	1.36
		Distichlis spicata		Large stand		0.33	0.48	0.53
Perennial herbaceous in drainage canals, Alexandria, Egypt	Rashed (2014)	*Phragmites australis*	FAO56-ET_o Floating lysimeters		0.82			
		Typha latifolia			0.79			
		Panicum repens			1.05			
		Pontederia crassipes			0.94			
		Lemna sp.			0.87			

Symbols, abbreviations and acronyms are given in Abbreviation section

high $K_{c\ mid}$, larger than or close to 1.0, and lower values of $K_{c\ ini}$ and $K_{c\ end}$, thus with a K_c curve like the classical segments curve proposed by FAO (Doorenbos and Pruitt 1977). Grasses show a $K_{c\ avg}$ close to 1.0 and a behavior like that of the reference grass. Diverse vegetation occurs by the Fenéka pond (Anda et al. 2015) to which correspond varied $K_{c\ avg}$ values. The highest $K_{c\ avg}$ values there, of 1.18, refer to emergent vegetation, mainly reed and cattail, and the smaller $K_{c\ avg}$ values are of woody deciduous trees and shrubs, 0.75 and 0.85. Coastal wetland plants also show high $K_{c\ mid}$ (Fermor et al. 2001; Jia et al. 2009). Information collected indicates a large daily variation of K_c values, mainly depending on the available solar energy, i.e., ET_c of non-riparian wetlands is not water limited but energy limited.

Table 3 groups the selected case studies relative to sites with less-cold winter climate and with relatively high ET during the non-growing season. Most cases refer to Florida and California while the other cases are for diverse countries, regions. The dominant vegetation is varied, with cattail being the most occurrent in Florida and San Joaquin Delta, while reed is most common in Turkey, Germany, Italy, and China, where the temperature difference between summer and winter is notably higher. Cattail and reed $K_{c\ mid}$ values, approximately 0.80 to 1.20, are nearly similar to those grown in cold and freezing winters (Tables 1 and 2) likely because summer weather environment is warm/hot for all three cases. Average K_c values for the growing season are generally smaller than $K_{c\ mid}$ for the same period. Naturally,

Table 5 Field observed crop coefficients for peat bogs

Identification	Reference	Dominant species	Method for estimating ET_o and $ET_{c\ act}$	Actual crop coefficient derived from field observations				
				Conditions	$K_{c\ avg}$	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
Egbertsdijksvenen bog, Eastern Holland	Moors et al. (1998)	*Molinia caerulea, Sphagnum* spp.	Makk. ET_o BREB	Jun–Sep		0.50	1.16	0.56
Mountain peat bog of Santa Bárbara, Terceira Island, Azores, Portugal	Fontes et al. (2006)	*Sphagnum* spp., *Calluna vulgaris, Juniperus brevifolia*	FAO56-ET_o Basin WB	Annual		0.50	0.80	0.45
Mer Bleue bog in SE Ontario and Degerö Stormyr fen in Sweden	Granath et al. (2016)	*Sphagnum* spp.	Penman ET_o Fluxnet & EC	Crop season	0.88			
Heather vegetation in Bruntland Burn, Scottish Highlands	Wang et al. (2017)	*Sphagnum* spp., *Molinia caerulea*	FAO56-ET_o MEP model	Shrubs, moss, grasses	0.94			
Peat bog in the Harz Mountains, Germany	Gerling et al. (2019)	*Sphagnum magellanicum Eriophorum angustifolium, Molinia caerulea*	FAO56-ET_o EC	July and August	0.84			
Peatland in the Zoige basin, Yellow River Source, China	Li et al. (2020)	*Carex mulieensis, Carex meyeriana, Kobresia tibetica, Blysmus sinocompressus*	FAO56-ET_o Modified from Kpan	May–Nov		0.70	1.10	0.62
Watchbed Creek mountain peatland, Victorian Alpine Nat. Park, Australia	Gunawardhana et al. (2021)	*Sphagnum cristatum, Richea continentis, Baeckea gunniana, Empodisma minus*	FAO56-ET_o EC	Oct–May	0.78	0.50	1.05	0.80

Symbols, abbreviations and acronyms are given in Abbreviation section

$K_{c\ avg}$ for the growing season are notably higher than $K_{c\ avg}$ relative to the non-growing season.

The values for the initial and end stages of reed and cattail are evidently smaller than $K_{c\ mid}$ but may be close to that value. Likely this occurs when climate favours ET and a rapid initiation and/or energy keeps available during senescence. Generally, they are not very different of those reported for cold winter climates, likely because respective climate conditions during the growing season are somewhat similar. *Cladium jamaicense* and *Cladium mariscus,* reported respectively by Mao et al. (2002) and Wu and Shukla (2014), have shown a K_c behaviour similar to cattail but larger K_c. The tule (or bulrush), reported by Howes et al. (2015) for the Kern River in California, has also similar K_c values. The invasive *Spartina alterniflora* has shown to dominate over the common reed, growing faster and more and having higher K_c values than reed.

Table 3 includes various associations of diverse plants. The one reported by Min et al. (2010) is quite varied resulting in medium values for K_c relative to the three crop stages, which is proxy of values for cattail in various sites. Moffett et al. (2010) reported about another association of plants adapted to salinity in an intertidal salt marsh, in San Francisco Bay, California, USA. The ecosystem $K_{c\ avg}$ is around 1.0, thus indicating a high response to the evaporative demand of the atmosphere. Another salt marsh in Newcastle, Australia (Hughes et al. 2001), with different vegetation, shows smaller $K_{c\ avg}$ values.

Table 3 includes reference to an experiment for evaluation of various hydrophyte plants that have potential to be used as bioenergy crops (Barco et al. 2018). Results do not characterise any wetland because correspond only to single species; K_c values are high because the experimental sites were small and could be affected by local advection. However, these data (Barco et al. 2018) is important to recognize the ET demand of these plants.

Crop coefficients for wetlands in warm climates, that are often marked by aridity, including for wetlands near the sea and affected by salinity, are presented in Table 4. Vegetation tolerant to salts tends to dominate in coastal areas, while inland marshes also have salt tolerant plants. K_c values tend to be smaller in areas marked by salinity, but $K_{c\ mid}$

Table 6 Plants of wetland ecosystems: crop coefficients, plant height, flooding regime and wetland type (sources: cited references in Tables 1, 2, 3, 4 and 5 and http://www.worldfloraonline.org)

Scientific name	Common name	Conditions and climate	$K_{c\ avg}$	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$	Plant height (m)	Flooding regime	Wetland type
Carex spp.	Sedges	Temperate, cold, humid	0.90–1.10	0.85	1.15	0.80	0.80–1.30	Meadow	Marshes
Ceratophylum demersum	Foxtail	Central Europe, temperate-cold		1.00	1.10	0.95		Submerged	Ponds
Cladium mariscus	Sawgrass	Eurosiberian southern & N. America temperate humid	1.00		1.10		0.80 to 1.50, up to 3.00	Emergent	Lowland (fens, marshes and swamps (not wooded))
Distichlis spicata	Saltgrass	Sub-tropical, Med		0.25	0.55	0.40	0.40 to 0.90	Emergent	Salt marshes, intertidal salt marshes
Glyceria maxima	English water grass	Temperate, sub-humid	1.00				0.80–2.00	Emergent	Swamps along streams and ponds
Iris pseudacorus	Yellow iris	Temperate and Med., sub-humid	1.00				0.70–1.50	Emergent	Swamps and shallow water along streams and ponds
Lemna sp.	Duckweed	Temperate, Med., and Trop	0.85					Submerged or, floating	Quiet bodies of water (ponds)
Lythrum salicaria	Purple lythrum	Temperate -Med sub-humid	1.00–1.40				0.30–1.50	Emergent	Wet meadows, fens, ditches
Panicum repens	Torpedograss	warm-to-hot climates	1.05				0.60–1.25	Meadow	Wet pastures, lakeshores, freshwater & brackish marshes, wet sandy soils
Phragmites australis	Common reed	Temp., cold (Apr–Oct)	0.70	0.45	0.80	0.60	1.1–4.0	Emergent	Marshes, streams and seeps; shores of standing and slow-flowing waters; riverbeds
		Temp., standing water	1.15	1.00	1.30	1.00			
		Temp., moist soil cond	0.95	0.80	1.20	0.80			
		Temp., large stand (Apr–Oct)	1.00	0.80	1.10	0.80			
		Temp., small stand (Apr–Oct)	1.20	0.85	1.35	0.90			
		Cold win. large stand (Mar–Nov)	1.05	0.60	1.15	0.70			
		Cold win. small stand (Mar–Nov)	1.20	0.65	1.35	0.90			
Pontederia crassipes	Water hyacinth	Hot and dry	0.95				0.20–0.60	Floating	Ponds, lakes, rivers or streams
Prionium serratum	Palmiet	Sub-tropical	1.05	0.95	1.10	1.00	2.0	Emergent	Streams and rivers, often in dense stands

Table 6 (continued)

Scientific name	Common name	Conditions and climate	$K_{c\ avg}$	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$	Plant height (m)	Flooding regime	Wetland type
Schoenoplectus acutus	Tule	Cold winter		0.85	1.25	0.90	1.0–3.0	Emergent	Lakes and pond shores, wet ditches, fens, calcareous to brackish marshes
Salicornia depressa	Glasswort	Sub-tropical, Med	1.14				0.10–0.70	Emergent	Intertidal salt marsh
Scirpus lacustris	Bulrush	Large stand	0.85	0.70	1.10	0.50	1.00–2.50	Emergent	Standing and slow-flowing waters
		Small stand		0.50	1.35	0.50			
Spartina alterniflora	Smooth cordgrass	Apr–Oct		0.95	1.15	0.80	1.0 to 2.0 up to 3.0	Emergent	Coastal salt-marshes, mainly intertidal, smaller at the upper tidal margins
Sporobolus foliosus	California cordgrass	Sub-tropical, Med	1.02				Up to 1.50	Emergent	Intertidal salt marsh
Suaeda heteroptera	Seepweed	Cold winter, hot summer	1.02		1.22		0.60	Emergent	River delta marsh, saline and coastal soils
Typha latifolia, *Typha* spp.	Cattail	Large stand	1.00	0.80	1.15	0.90	1.5–3.0	Emergent	Standing, muddy waters up to approx. 1.5 m deep
		Small stand		0.80	1.35	0.85			

values > 0.50. However, higher values are achieved when the vegetation is salt tolerant, while elsewhere most plants show a $K_{c\ mid}$ value of 1.00 to 1.20 approximately, and $K_{c\ avg}$ slightly smaller. Reported K_c values indicate higher values for small stands due to local advection.

The selected case studies in Table 4 refer to both arid and semi-humid climates, such as the swamps of the upper Nile and coastal wetlands of Maputaland, South Africa. Relative to the enormous wet savanna of Pantanal in Central Brazil, $K_{c\ avg}$ data refers only to a forest. Relative to the vegetated drainage channels in Northern Egypt, $K_{c\ avg}$ is reported for diverse species ranging 0.79 to 1.05. Despite the variability of vegetation, cattail, reed and tule are present in various sites with $K_{c\ mid}$ values generally > 0.90.

Table 5 refers to peat bogs of varied origins and with the presence of moss, with the exception of a high mountain peatland area near the source of the Yangtse, in West China, where the dominant plants are *Carex* and *Kobresia* grasses. The case studies refer to different countries and environments, most cases in mountain sites, including in an island of Azores, and one case study in lowland, in the Netherlands. Apart from moss, the dominant vegetation is very diverse. *Molinia caerulea* is the most common plant in North Europe bogs, contributing to ecosystem $K_{c\ mid} > 1.0$, while the site of Santa Bárbara Mountain, Azores, has a $K_{c\ mid} = 0.80$ dictated by *Calluna vulgaris*. This lower value is likely due to the effects of high cloudiness limiting the energy available for evapotranspiration.

Table 6 presents typical K_c values and characteristics of vegetation recorded from the selected papers quoted in Tables 1, 2, 3, 4 and 5. The listed plants include only those that could be individuated through the papers, mainly in terms of K_c values and characteristics influencing those values. The K_c values tabulated are assimilated to standard values, thus generally assumed not stressed; smaller values are likely to be found for similar vegetation. The tabulated aspects characterizing the plants have various sources following a wide internet search, mainly http://www.worldfloraonline.org.

While data on K_c in Tables 1, 2, 3, 4 and 5 aims at supporting selection of K_c values by users in relation to the climate, vegetation and type of reported wetlands, K_c values in Table 6, in addition to be also used in the practice, aim at better characterizing vegetation dominating in the various reported wetlands. This type of characterization could be continued in future. The $K_{c\ mid}$ values of emergent plants are generally in the range of 1.10 to 1.20 (Table 6) while small stands may have values 0.20–0.25 greater than large stands due to local advection. For common reed a difference in K_c values of about 0.10 between growing in standing water or

Table 7 Actual crop coefficients of riparian vegetation in regions of cold winter and warm summer

Identification	Reference	Dominant species	Method for estimating ET_o and $ET_{c\ act}$	Actual crop coefficient derived from field observations				
				Conditions	$K_{c\ avg}$	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
Pingchuan oasis, middle Heihe River basin, Gansu, China	Liu et al. (2010)	*Populus gansuensis*	FAO56- ET_o EC, SWB gravim		1.02	0.53	1.23	1.09
		Haloxylon ammodendron			0.45	0.20	0.61	0.61
		Calligonum mongolicum			0.42	0.21	0.57	0.53
		Tamarix ramosissima			0.48	0.20	0.67	0.65
		Bassia dasyphylla			0.44	0.21	0.65	0.54
		Suaeda glauca			0.47	0.22	0.67	0.55
		Phragmites australis			0.46	0.23	0.62	0.55
Ejina oasis, Heihe river, Inner Mongolia, China	Hou et al. (2010)	*Populus euphratica*	FAO56-ET_o BREB	May–Sep		0.40	0.63	0.23
Hyper arid Low Tarim basin, Xinjiang, China	Yuan et al. (2014)	*Tamarix* spp., *Populus euphratica*	FAO56- ET_o EC, SWC-FDR	Apr–Oct	0.20 0.25			
Oasis-desert transition between the Badain Jaran Desert and the Zhangye Oasis, Heihe river basin, China	Zhao and Zhao (2014)	*Haloxylon ammodendron, Elaeagnus angustifolia, Tamarix ramosissima, Bassia dasyphylla, Halogeton arachnoideus, Suaeda glauca*	FAO56-ET_o P-M comb model	Vegetation cover of 6%		0.10	0.45	0.20
Tamarisk in saline Middle Heihe River valley, Gansu, China	Li et al. (2015)	*Tamarix ramosissima*	FAO56-ET_o HYDRUS-1D	Shallow GW		0.55	1.05	0.55
Desert riparian in Lower Tarim basin, Xinjiang, China	Yuan et al. (2016)	*Tamarix* spp., *Populus euphratica*	FAO56-ET_o EC, SWC-FDR Model ET-LAI	Thicket Woodland	0.55 0.54			
Fiber riparian plants, Tarim delta, NW China	Thevs and Rouzi (2015)	*Apocynum pictum*	FAO56-ET_o Energy balance	May–Oct Deep GW (5 m)		0.24	0.26	0.10
Middle reaches of Tarim River, China	Thevs et al. (2017)	*Populus euphratica*	FAO56-PM BREB	Iminqak site	0.74	0.59	0.81	n/r
		Tamarix ramosissima		Qongaral site	0.32	0.30	0.35	n/r
Alxa Desert, Low Heihe river, China	Yu et al. (2017)	*Tamarix ramosissima*	FAO56-ET_o EC and SF	May–Oct		0.17	0.74	0.19
Low Heihe River, Gansu, China	Yu et al. (2018)	*Tamarix ramosissima*, *Populus euphratica*	FAO56- ET_o EC and EB	May–Sep	0.48 0.63	0.14 0.57	0.73 0.73	0.52 0.56
Edge of Gurbantunggut Desert, Xinjiang, China	Jiao and Hu (2023)	*Haloxylon ammodendron*	FAO56-PM BREB & SWB	GW down to 8 m	0.22	0.25	0.22	0.22
Woodland and shrubs in Zhang-gutai, Liaoning, China	Zheng et al. (2012)	*Pinus sylvestris* var. *mongolica*, *Populus* spp.	FAO56-ET_o SWB-CROPWAT, RS	Mongolica pine		0.50	0.62	0.55
				Poplar		0.75	0.87	0.65
				Shrubs		0.15	0.89	0.65
Salt affected GW fed vegetation in Hetao, Inner Mongolia, China	Ren et al. (2017)	*Tamarix chinensis*	FAO56-ET_o dual K_c & Hydrus-1D	May–Sep		0.15	0.70	0.40

Table 7 (continued)

Identification	Reference	Dominant species	Method for estimating ET_o and $ET_{c\ act}$	Actual crop coefficient derived from field observations				
				Conditions	$K_{c\ avg}$	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
GW fed meadow in Horqin Sandy Land, Inner Mongolia, China	Wu et al. (2016)	*Leymus chinensis*	FAO56-ET_o SWB-FDR, SIMDualKc	Apr–Oct		0.50	0.75	0.60
Riparian Tugai forest, shrubs and reeds, Amudarya Valley, Turkmenistan	Thevs et al. (2015)	*Populus euphratica, Tamarix* spp., *Phragmites australis, Halostachys caspica*	FAO56-ET_o RS S-SEBI	Tugai forest: dense, WTD < 3 m sparse, WTD > 3 m	1.02 0.76			
				Tugai shrub	0.26			
				Reed	0.84			
Riparian fen wetland in the lower River Gjern, in Jutland, Denmark	Andersen et al. (2005)	*Alopecurus pratensis, Deschampsia caespitosa, Glyceria maxima, Alnus glutinosa*	FAO56-ET_o BREB	Apr–Sep		1.40	1.24	1.30
Fenéka pond, Kis-Balaton Lake, Hungary	Anda et al. (2015)	*Festuca rupicola, Arrhenatherum elatior, Alopecurus pratensis*	FAO56-ET_o Mod. DL	Apr–Sep		0.90	1.10	0.90
Riparian forest, Kern River, CA, USA	Howes et al. (2015)	*Quercus douglasii*	FAO56-ET_o METRIC	Large stand		0.80	1.15	1.00
Putah Creek, Sacramento Valley, CA, USA	Grismer (2018)	*Populus* spp., *Salix* spp.	ASCE-ET_o Mass balance	Mixed veg.year		0.10	0.80	0.10
Riparian trees in Platte river, Odessa & Gottenburg, Nebraska, USA	Landon et al. (2009)	*Populus* spp., *Cornus* spp.	Mod Penman SWB-TDR, EC and SF	Odessa, year		0.18	0.39	0.10
		Populus spp., *Juniperus* spp.		Gottenburg, year		0.19	0.43	0.10
Riparian grass & woodland at Platte River, Nebraska USA	Hall and Rus (2013)	*Poa pratensis*	FAO56- ET_o EC	Elm Creek		0.28	0.63	0.20
		Populus spp.,		Odessa		0.25	0.75	0.18
Platte River basin, Central Nebraska, USA	Irmak et al (2013)	*Phragmites australis*	ASCE-ET_r BREB and REBS	$\mathbf{K_{cb}}$	**0.72**			
		Populus deltoides		$\mathbf{K_{cb}}$	**0.65**			
		Salix amygdaloides		$\mathbf{K_{cb}}$	**0.83**			
Trees and grasses in Shoemaker Island, Platte River, NE, USA	Yue et al. (2016)	*Populus* sect. *Aigeiros, Juniperus virginiana*	FAO56-ET_o $ET_{c\ act}$ from WTD and specific tield	High WTD Deeper WTD	0.80 0.15			
		Panicum virgatum, Bromus inermis		High WTD Deeper WTD	0.70 0.10			
Cibola National Wildlife Refuge, CA	Nagler et al. (2013)	*Tamarix ramosissima*	FAO56-ET_o MODIS-EVI	Non-dormant season	0.46			
Platte River, NE;		*Phragmites australis*			0.63			
San Pedro River, AZ		*Prosopis* spp.			0.60		0.85	
Bosque del Apache, Middle Rio Grande, New Mexico, USA	Nichols et al. (2004)	*Tamarix ramosissima*	B-C ET_o EC	Apr–Oct		0.30	1.25	0.80

Table 7 (continued)

Identification	Reference	Dominant species	Method for estimating ET_o and $ET_{c\ act}$	Actual crop coefficient derived from field observations: Conditions	$K_{c\ avg}$	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
Trees & shrubs in Middle Rio Grande, New Mexico, USA	Allen et al. (2005)	*Populus* spp.	ASCE- ET_o METRIC-Landsat5	Large stands	0.77	0.59	0.91	0.72
		Tamarix spp.			0.62	0.43	0.77	0.68
		Elaeagnus angustifolia			0.82	0.62	0.94	0.75
		Salix spp.			0.72	0.52	0.86	0.70
Bosque del Apache Middle Rio Grande, New Mexico, USA	Bawazir et al. (2009)	*Populus* spp.	ASCE- ET_o ASTER-VI and EC	Feb.–Sep	0.51	0.28	0.76	0.78
		Tamarix spp.		Feb.–Sep	0.60	0.44	0.94	0.35
Riparian trees in California and New Mexico, USA	Howes et al. (2015)	*Salix* spp., *Populus* spp., *Elaeagnus angustifolia*	FAO56- ET_o METRIC	CA + N Mexico		0.67	1.09	0.83
				N Mexico 1		0.72	1.12	0.89
				N. Mexico 2		0.74	0.99	0.92

Symbols, abbreviations and acronyms are given in Abbreviation section;

Bold values refer to basal crop coefficients values

in moist soil was detected. Lower K_c values are defined for emergent plants in salty wetlands, such as coastal marshes, with the smallest value for salt grass in intertidal marshes. Low values are also assigned to submerged or floating plants in ponds. Emergent grasses in salty marshes have K_c slightly lower than in meadows. These derived K_c values may be usable for establishing practical soil water or basin balances to estimate wetland evapotranspiration, perform the water balance and estimate the water requirements for conservation of the ecosystem, as well as to help detecting water supply deficits.

Crop coefficients for wetland riparian ecosystems

Riparian ecosystems occur in less widespread climates and environments than wetlands, being more frequent in temperate and warm climates marked by aridity. Their vegetation, contrarily to that of wetlands, does not require to live in standing water or in moist soil, but uses the close-by rivers' water or a variably deep flowing groundwater. Therefore, riparian vegetation is quite different from that in wetlands, mainly consisting of trees (e.g., cottonwood and willow) and large or small shrubs (e.g., tamarisk and mesquite), namely having deep roots. Plants nomenclature, morphology and ecology are those referred in http://www.worldfloraonline.org. Differently from wetlands, the available water may vary much from year to year and season to season depending upon the variations in precipitation, basin runoff (RO) and water infiltration and recharge of groundwater (GW), as well as with water withdraws from the river or groundwater for human and societal uses, typically for irrigation.

Table 7 presents the K_c values and information from papers relative to riparian vegetation ecosystems occurring in regions of cold winter climates and warm to hot summer. Most studies refer to the arid/semiarid regions of northwest China and south/southwest of USA. Other studies refer to UK, Denmark, Hungary, and Turkmenistan. That diversity of studies and sites shall provide a good vision of riparian ecosystems in the North Hemisphere. The dominant vegetation in NW China consists of tamarisk and saxaul, two large shrubs, and cottonwood and Mongolica pine as main trees, but tamarisk and cottonwood are by far dominating. Both tamarisk and cottonwood are also dominating in north America, together with other shrubs and trees, such as the Russian olive, a large shrub, and willow and juniper trees. The $K_{c\ mid}$ values of tamarisk and cottonwood in Chinese sites are generally less than 1.0 but when water is not limiting are greater, 1.23 in case of *Populus gansuensis.* Other trees and shrubs commonly have values of $K_{c\ mid} < 0.70$, i.e., riparian plants mostly are water limited.

Table 8 Actual crop coefficients of riparian vegetation in temperate and hot climates

Designation and location	Reference	Dominant species	Method for estimating ET_o and $ET_{c\ act}$	Actual crop coefficient derived from field observations				
				Conditions	$K_{c\ avg}$	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
Lower Colorado river at Havasu National Wildlife Refuge, AZ, USA	Westenburg et al. (2006)	*Tamarix* spp.	FAO56-ET_o BREB	High-density		0.22	0.76	0.22
		Prosopis spp., *Tamarix* spp., *Distichlis spicata*, *Pluchea sericea, Baccharis* spp.		Mixed vegetation		0.30	0.53	0.30
		Pluchea sericea		Dominant		0.20	0.56	0.20
Riparian shrubs and trees, Lower Colorado River, Blythe, CA, & Havasu, AZ, USA	Glenn et al. (2011)	*Tamarix* spp.	FAO56-ET_o Flux towers, MODIS-EVI, GVMI & SF	6 sites, Blythe	0.48–1.30			
		Pluchea sericea		Havasu	0.60			
		Tamarix spp.		Havasu	0.65–0.80			
		Populus spp.		Blythe	1.15			
Mixed vegetation, Cibola National Wildlife Refuge, Low Colorado River, USA	Khand et al. (2017)	*Tamarix* spp., *Prosopis velutina, Populus* sp., *Salix* sp., *Pluchea sericea*	FAO56 ET_o RS: SSS-ET	Mixed vegetation	0.29 0.33 0.30 0.29		0.76	
Riparian vegetation Navajo Nation, Little Colorado River, USA	Nagler et al. (2023)	Riparian trees	B-C ET_o MODIS-EVI		0.37			
Mesquite trees at San Pedro River flood plain, AZ, USA	Scott et al. (2000)	*Prosopis velutina*	Penman ET_o BREB	May–Sep		0.17	0.41	0.48
Cottonwood in Lewis Springs (**LS**) & Boquillas (**BO**), San Pedro River, AZ, USA:	Gazal et al. (2006)	*Populus fremontii*	Penman ET_o SF	**LS**: permanent flow, WTD = 1.6 m		0.46	0.92	n/r
				BO: intermittent flow, WTD = 3.3 m		0.34	0.69	n/r
Riparian Forests, Mojabe river, CA, USA	Neale et al. (2011)	*T. ramosissima*	FAO56 ET_o SEBAL + TSM + Lidar system			0.15	0.48	0.15
		Populus spp.				0.15	0.62	0.15
		Mesophytes				0.15	0.47	0.15
		Coniferous				0.15	0.32	0.15
		Arundo sp.				0.15	0.49	0.15
		Desert scrub				0.15	0.27	0.15
Toenepi stream, Waikato, N. Zealand	Sarwar et al. (2022)	Pasture with stream bording trees &shrubs	FAO56-ET_o Water balance		0.92	0.85	0.94	0.80
Willows in SE New S. Wales, Australia	Doody et al. (2014)	*Salix fragilis*	Pan class A PMeq	Tea Garden Creek		1.19	0.93	1.21
		S. babylonica		Billabong Creek		1.60	0.95	1.61
Riparian savana in Groot Letaba River, NE South Africa	Gokool et al. (2017)	*Phragmites mauritianus, Ficus sycomorus, Philonoptera violacia, Diospyrus mespiliformis*	FAO56-ET_o EC and SEBS Landsat	Savana with mixed veget		0.40	1.20	0.40
Silala River, border of Bolivia and Chile	Suárez et al. (2023)	*Oxychloe andina, Deyeuxia* spp., *Parastrephia* spp., *Lilaeopsis macloviana*	FAO56-ET_o EC	Mixed reed, grass, shrubs and hydrophytes	0.62			

Symbols, abbreviations and acronyms are given in Abbreviation section

Typical riparian ecosystems using groundwater tables are those in an oasis and along the Heihe and Tarim rivers. having lower K_c values when salinity occurs and in downstream areas due to high water withdraw upstream. To note that *Apocynum pictum*, a fiber plant, is explored in the Tarim river inland delta but has a very small K_c value that results from low water availability due to upstream withdraw. K_c values are larger in the Liaoning region, where water is less limiting. Grass riparian vegetation is present in the Horqin sandy area, in Inner Mongolia, where groundwater is under the sandy dunes and showing in diverse small lakes; there, Chinese rye grass provides for pasture with a $K_{c\ mid}$ value of 0.75. In all cases results show the K_c curves following the four segments FAO K_c curve.

The crop coefficients relative to the southern riparian vegetation of USA (Table 7), like the previously referred riparian areas in China, are mostly < 1.00 and generally smaller than those of wetlands in similar climates (Tables 3, 4 and 5). Likely, this happens because available water for this vegetation is insufficient to match full water requirements, i.e., evapotranspiration is water, non-energy, limited in most riparian areas. These regions are marked by aridity. K_c values for riparian vegetation in cold winter and hot summer climates are quite similar to those analysed before. Most cases of USA are from the Lower Colorado river basin where dominant vegetation consist of cottonwood, willow, mesquite, tamarisk, thus woody plants able to withdraw water from much larger depths than herbaceous, also present in wetlands.

Table 7 also includes riparian zones from other countries: The Tugai forest and associated shrubs of the Amudarya Valley of Turkmenistan, fen wetland in the lower River Gjern, in Jutland, Denmark, and the Fenéka pond, Kis-Balaton Lake, in Hungary. The Tugai forest has *Populus euphratica* as dominant and the main shrub is *Halostachys capsica*; the first has a high $K_{c\ avg}$ due to favourable GW withdraw, while the latter is sparse throughout dryer areas. The fen in Jutland has diverse herbaceous vegetation with quite high K_c values since the area has much rainfall, quite distinct from the other referred riparian areas. The Hungarian study, is also from an area with relatively high rainfall, resulting that the vegetation, predominantly herbaceous, have a high $K_{c\ mid}$ of 1.10. The European riparian areas result very distinct of the previously presented riparian ecosystems marked by aridity.

The riparian ecosystems relative to hot climates (Table 8), mostly in South USA, show $K_{c\ mid}$ and $K_{c\ avg}$ values generally smaller than 0.80, which reflect the occurrence of water stress since the vegetation has access to a limited amount of water that only partially satisfies its needs, as it is expected from riparian vegetation in areas with a large evaporation demand of the atmosphere. In the Low Colorado River basin and the San Pedro River valley, the more frequent dominant vegetation is *Tamarix* spp., *Prosopis velutina*, *Populus* spp., *Salix* spp. and, where vegetation is scarcer, the *Pluchea sericea*. Higher K_c values are for *Populus fremonti* but depending upon the water table depth.

Other selected papers refer to the Southern Hemisphere, namely the Silala river, in the border area between Bolivia and Chile, also arid, where mixed reed, grass, shrubs and hydrophytes show $K_{c\ avg} = 0.62$, also somewhat low. Three fruit trees—*Ficus sycomorus, Philonoptera violacia and Diospyrus mespiliformis*—are part of the riparian savanna by the Groot Letaba River, NE South Africa. The ecosystem K_c curve is similar to those of Mediterranean orchards (Pereira et al. 2023b). The site in New Zealand refers to a pasture close to a small stream with bordering trees and shrubs, which K_c curve, influenced by rainfall, is similar to those of grasslands reported by Pereira et al. (2023a). The cases for Australia refer to willows bordering two creeks that provide for abundant water, particularly during the initial and end-season stages, which make the segmented K_c curve to be inverted relative to the common one, as it happens with the olive in Mediterranean climates (Pereira et al. 2023b).

Table 9 presents the K_c values and selected characteristics of vegetation reported in the selected papers and that could be individualized. Related references are the same referred in Tables 7 and 8, as well as the online flora (http://www.worldfloraonline.org). The reported characteristics of the identified plants include the rivers regimes, permanent or temporary, and the groundwater table conditions: shallow, intermediate (1 to 5 m depth) and deep (5 m). It can be seen that vegetation identified as using permanent river water and/or shallow groundwater have larger $K_{c\ mid}$ and/or $K_{c\ avg}$. Contrarily, plants having access to temporary river flow and or deeper water tables have smaller K_c. Nonetheless, tabulated K_c values are just related with the conditions reported in the selected papers, which may be different in other locations. Therefore, despite the K_c values tabulated were accurately derived, their values have to be assumed as indicative, to be used with caution until new research provides for better values. Anyway, they can be used for in the practice for computing plant evapotranspiration when an estimate of the FAO-PM ET_o is available, as well as, to compute the water balance when other water outputs and inputs are known.

Conclusions

The current review study collected for the first-time crop coefficients reported in published research on evapotranspiration from riparian and non-riparian wetland vegetation

Table 9 Crop coefficients of riparian plants (sources: references in Tables 7 and 8, and http://www.worldfloraonline.org)

Scientific name	Common name	Uses, conditions and climate	Ranges of Kc derived from field observations				Plant height (m)	River flow regimen		Maximum GW depth (m)			Salt conditions
			$K_{c\ avg}$	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$		perm	temp	< 1	1–5	> 5	
Apocynum pictum	Indian hemp, kendyr	Fiber plant, cold to temperate, aridity		0.24	0.26	0.10	2.0	–	–	–	Yes	–	Saline-alkaline tolerant
Artemisia tridentata	Big sagebrush	Indicator of productive sites; arid to semi-arid; April–December		0.35	1.20	0.35	3.0	Yes	–	–	Yes	–	Some ecotypes grow with salt-tolerant plants
Arundo donax	Giant reed	Phytoremediation of metal-contaminated soils; weed in Mediterranean region		0.30	0.70	0.30	3.0–5.0	–	Yes	Yes	–	–	Salty soils tolerant
Atriplex halimus	Saltbush	Phytoremediation plant in highly saline soils; warm regions; large stands		0.35	0.50	0.50	0.5–3.0	–	–	–	Yes	–	Mildly alkaline soils, can grow in very alkaline and saline soils
Bassia dasyphylla	Shaggy-leaved Bassia	Warm-temperate and subtropical zones; annual	0.45	0.20	0.65	0.55	0.1–0.5	–	–	Yes	–	–	Saline-alkaline locations
Calligonum mongolicum	Smartweed	Oasis deserts; prevent soil erosion	0.40	0.20	0.55	0.50	0.25–1.5	–	–	–	–	Yes	May grow in salty conditions
Carex spp.	Sedge	All conditions and climates		0.40	1.10	1.10	Up to 1.0	–	–	Yes	–	–	Not salty areas
Elaeagnus angustifolia	Russian olive	Fix nitrogen; drought and cold resistant	0.80	0.65	0.95	0.80	3.0–10.0	–	–	–	Yes	Yes	Prefers alkaline soils
Haloxylon ammodendron	Saxaul	Afforestation of arid areas; cold regions	0.45	0.20	0.60	0.60	2.0	–	–	–	–	Yes	Saline-alkaline soils
Leymus chinensis	Chinese rye grass	For grazing and forage; Apr–Oct		0.50	0.75	0.60	0.50–0.80	–	–	Yes	–	–	Not salty
Phragmites australis	Common reed	Alien invader, more common in wetlands	0.45	0.25	0.60	0.55	Up to 2.0	–	–	Yes	–	–	Fresh and brackish water
Pinus sylvestris var. mongolica	Mongolica pine	Eolic erosion control; cold climate		0.50	0.62	0.55	Up to 40	–	–	–	–	Yes	Not salty
Pluchea sericea	Arrowweed	Warm semi-desert	0.60	0.30	0.80	0.20	1.00–5.00	–	–	–	Yes	–	Not salty
Poa pratensis	Blue grass	Temperate, humid		0.28	0.63	0.20	0.10–1.20	Yes	–	Yes	–	–	Not salty, acid soils
Populus deltoides	Cottonwood	Gallery forests; temperate	0.75	0.55	1.00	0.70	Up to 50	–	Yes	–	Yes	–	Not salty, stream banks, acid
Populus euphratica	Euphrates poplar	Temperate and subtropical dry broadleaf	0.75	0.60	0.80	0.60	15.0		Yes	–	Yes		Not salty, mildly acid
Populus fremontii	Frémont's cottonwood	Water table depth, WTD≈1.6 m		0.45	0.90	0.45	25.0	Yes			Yes		Not salty
		WTD≈3.3 m		0.35	0.70	0.35			Yes		Yes		
Populus gansuensis	Cottonwood	Arid to semi-arid regions	1.00	0.55	1.20	1.10	12.0–35.0	–	Yes	–	–	Yes	Not salty
Populus spp.	Cottonwood	When water available is low		0.15	0.60	0.15	Up 30.0	–	Yes	–	–	Yes	Not salty
		When water available is high		0.70	1.15	0.90	Up 50.0	Yes	–	–	Yes	–	Not salty
Prosopis velutina	Velvet mesquite	Edible pods for human and wildlife; arid	0.33	0.15	0.40	0.50	9.0–15-0	–	Yes	–	–	Yes	Not salty; wide soil textures
Salix spp.	Willow	Source of salicylic acid; very cold to warm	0.80	0.55	0.95	0.75		–	Yes	–	Yes	–	Some varieties are salt-tolerant
Suaeda glauca	Saltwort	Seed oil; arid oasis and semi-arid land	0.50	0.25	0.70	0.55	Up 1.0	–	–	–	Yes	–	Saline-alkaline soils

Table 9 (continued)

Scientific name	Common name	Uses, conditions and climate		Ranges of Kc derived from field observations				Plant height (m)	River flow regimen		Maximum GW depth (m)			Salt conditions
				$K_{c\ avg}$	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$		perm	temp	<1	1–5	>5	
Tamarix spp.	Tamarisk, saltcedar	Dry areas	High density, wet	0.60	0.45	1.10	0.40	3.0–5.0	–	Yes	–	Yes	–	Saline-alkaline, brackish and fresh water
			Medium density	0.60	0.40	0.75	0.65	3.0	–	Yes	–	Yes	–	
			Low density, low wet	0.32	0.30	0.45	0.30	2.0					Yes	

ecosystems. This collection of information revealed consistent when comparing various types of wetlands and riparian ecosystems, particularly when comparing their K_c values. In fact, the collected K_c values are higher or lower according to the water availability recognizable through the papers descriptions and the water related characteristics of the identified plants and/or the online flora referred to in Tables 6 and 9. Considering the criteria used for collection of information as described in "Material and methods" section, the coherence observed in the tabulated data allows to assume confidence on the K_c values herein tabulated. The analysis and collection of K_c curves was not intended to be performed but may consist of future challenging research.

The tabulated K_c values are usable as default values for assessing the evapotranspiration of non-monitored wetland/riparian ecosystems and performing the respective water balances at various scales. For monitored ecosystems, the tabulated K_c may serve for comparing with locally collected data and, thus, testing the quality of related results. However, such use of the derived K_c requires the computation of the FAO-PM reference evapotranspiration since K_c values refer to this grass ET_o. This comparison and test of results may be applied for whatever approach used for monitoring ET and the water balance. The simple computation of K_c from the fraction of ground cover and vegetation height, the A&P approach (Allen and Pereira 2009; Pereira et al. 2021), may be of great interest for monitoring wetlands and riparian ecosystems due to its simplicity and non-requiring but simple instrumentation. Research for improved and extended monitoring of ET and water balance of wetlands is nevertheless required.

Tabulated K_c values resulting from this review study may help understanding when evapotranspiration of a given ecosystem is water or energy limited and, consequently, may support decisions of water management authorities relative to the conservation or the betterment of wetlands, including riparian ecosystems. When the dynamics of ET_c and of the water balance are known it is also easier to assess the ecosystems services, particularly those that relate with the water availability and to adopt appropriate water governance policies and measures,

It is well known that the search for water in regions marked by aridity led to the impoverishment and decrease of water available for life in riparian stands and wetlands. The quantification of water requirements using the K_c-ET_o approach may better help to recognize the stress produced, specially under drought, and to define measures that shall avoid the progressive decline of wetlands and riparian zones. This is particularly relevant when aiming to control the appropriation of wetlands water for irrigation. Research aimed at understanding the role of water in wetlands and riparian ecosystems is much needed, namely in combination with water uses for irrigation, and mainly relative to the sustainability of communities practicing agriculture, recollection, and beneficiating of ecosystem services.

This study allows comparison of a wide number of wetland and riparian ecosystems, mainly in terms of vegetation and evapotranspiration crop coefficients. Such a comparison is important because although riparian and non-riparian wetland ecosystems may have great similarities, they also have important differences. Using the $K_c - ET_o$ approach for that purpose is likely appropriate. Moreover, the above innovation may be developed in combination for both ecosystems, while at the same time research may support ecosystem services.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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