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REVIEW

Actual and standard crop coefficients for semi-natural and planted grasslands and grasses: a review aimed at supporting water management to improve production and ecosystem services

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Abstract

Natural and planted grasslands play a very important role in agriculture as source of various ecosystem services, including carbon sequestration and biodiversity, and are responsible for a large fraction of agricultural water use in rainfed and irrigated fields. It is, therefore, relevant to precisely know their water use and vegetation requirements with consideration of relevant climate, from extremely cold, dry, with long winter seasons, to tropical humid and hot climates, thus with a large variability of vegetation. Semi-natural grasslands are basically used for grazing and mainly refer to highland pastures and meadows, steppes, savannas, pampas, and mixed forest systems. The FAO method to compute crop (vegetation) evapotranspiration (ET_c) through the product of a crop coefficient (K_c) by the reference evapotranspiration (ET_o) is adopted. The selected papers were those where actual ET_c ($ET_{c\ act}$) was derived from field observations and ET_o was computed with the FAO56 definition, or with another method that could be referred to the former. Field derived $ET_{c\ act}$ methods included soil water balance, Bowen ratio and eddy covariance measurements, as well as remote sensing vegetation indices or surface energy balance models, thus reviewed $K_{c\ act}$ ($ET_{c\ act}/ET_o$) values were obtained from field data. These $K_{c\ act}$ refer to initial, mid-season and end season ($K_{c\ act\ ini}$, $K_{c\ act\ mid}$, $K_{c\ act\ end}$) when reported values were daily or monthly; otherwise, only average values ($K_{c\ act\ avg}$) were collected. For cases relative to cold or freezing winters, data refer to the warm season only. For grasses cut for hay, $K_{c\ act\ ini}$, $K_{c\ act\ mid}$, and $K_{c\ act\ end}$ refer to a cut cycle. $K_{c\ act}$ values rarely exceeded 1.25, thus indicating that field measurements reported did respect the available energy for evaporation. Overall, $K_{c\ act\ mid}$ for semi-natural grasslands in cold climates were lower than those in hot climates except when available water was high, with $K_{c\ act\ mid}$ for meadows and mountain pastures generally high. Steppes have $K_{c\ act\ mid}$ values lower than savannas. Grasses commonly planted for hay and for landscape generally showed high $K_{c\ act\ mid}$ values, while a larger variability was observed with grasses for grazing. The collected $K_{c\ act}$ values were used to define standard K_c values for all grassland and grasses. Nevertheless, the tabulated $K_{c\ act}$ are indicative values of K_c to be used for actual water management purposes and/or irrigation scheduling of planted grasslands. It is expected that a better knowledge of the standard and/or indicative K_c values for a wide variety of grasslands and grasses will support better management aimed to improve grass productivity and ecosystem services, including biodiversity and carbon sequestration.

Introduction

Grassland is a main biome in Earth, occurring in every country or region, and having a great variability in relation to climate, landforms and elevation, environmental conditions, use and management. It includes rangelands, shrublands, pastureland, and cropland sown with pasture. Regional descriptions of grasslands of various types are provided in the FAO book edited by Suttie Reynolds Batello (2005). A recent classification and world mapping of grassland types, also referring to their biodiversity, has been provided by Dixon et al. (2014). The analysis by Seo (2021) reports many famed grasslands including the Pampas, the Llanos,

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the Prairie, the Steppe, the Savannas, and the Rangelands. The importance of grasslands is well recognized.

Grasslands account for 26% of the world's global ice-free land area (Lorenz and Lal 2018), corresponding to the second greatest land use in the Earth (Lü et al. 2022), while forest land accounts for about 30%, and cultivated land for 12%. However, other authors considered that "grassland is the largest terrestrial biome on Earth" (Hobohm et al. 2021), accounting for up to 40% of the terrestrial area (Petermann and Buzhdygan 2021; Seo 2021). There are different concepts of grassland, e.g., with Dixon et al. (2014) defining grassland as a non-wetland type with at least 10% vegetation cover, dominated or co-dominated by graminoid and forb growth forms, and where the trees form a single-layer canopy with either less than 10% cover and 5 m height (temperate) or less than 40% cover and 8 m height (tropical). However, these limitations let out several semi-natural grasslands such as those of Mediterranean regions. Hobohm et al. (2021) state that grasslands support the livelihoods of 1 billion people with pastoralism (rising of livestock) with 20 million km^2 of grassland used for livestock feed production and for a variety of ecosystem services. Lü et al. (2022) pointed out the case of China, which has the second largest grassland area in the world, representing about 41% of China's national territorial area. Mongolia has a smaller grassland area, but it corresponds to 83% of its land area (Angerer et al. 2008). The overall importance of grassland is therefore evidenced, which justifies the attention of many researchers to improve their use for livestock feed production and for ecosystem services.

The research studies relative to evapotranspiration (ET) cover many planted and semi-natural grasslands, as well as grasses, graminoids, and legumes used for planted grasslands and lawns. ET studies very often aim at assessing climate change impacts and future coping measures, or are relative to hydrologic and water resources assessments, particularly when referring to semi-natural grasslands. Studies focusing on management mostly refer to planted permanent grasslands for hay and grazing, namely when irrigated, and include water–grass–yield relationships. Research on grassland management focusing on ecosystem services is rare but many studies intend to recognize specific ecosystem services. It is well known that grasslands play an important role in ecological environment protection and animal husbandry development (Lü et al. 2022), but ecosystem services commonly identified often have relations with water despite these aspects are evaluated with a low value degree (Kang et al. 2020; Liu et al. 2022a). High valued ecosystem services refer to biodiversity, carbon sequestration, soil erosion control, and soil fertility enhancement, mainly when grass legumes are used. Runoff is retarded by the vegetation, thus favoring soil infiltration, which is also larger because grass cover impedes crust formation, therefore increasing water storage in the soil and improving water availability. Other commonly reported services include purifying chemical fertilizers and pesticides, and regulating groundwater, mainly in lowlands, while contributing to climate regulation, and extremes mitigation are also mentioned. Recreation, snow sports, and landscape aesthetics are extremely important ecosystems services in mountain areas of Europe and northern America, contrarily to other regions. Depending on the type and management of the grasslands, biodiversity and carbon fixation are quite relevant services, often object of research, namely in relation with the degradation of grasslands (Lal 2018; Hobohm et al. 2021).

According to Lal (2018), anthropogenic activities have affected about 40% of earth's surface, and almost 92% of the natural grasslands and ecosystems, which have been converted to human use as grazing and croplands. Bonanomi et al. (2019) added that protecting forests at the expense of semi-natural grasslands can lead to the open-habitat loss of the Brazilian Cerrado biome. Hobohm et al. (2021) referred, as causes for degradation of grasslands, the expansion of urban areas, tree plantations, use of mineral fertilizers and pesticides, suppression of natural fires, over- and under-grazing, and intensification of use. Reforms of agri-environmental policies have aimed at incorporating environmental objectives into agriculture, such as biodiversity and carbon (C) sequestration in grasslands. However, many threats remain, "in both the now-fragmented areas of agriculturally improved productive lowlands" and in the marginal areas of Europe, where traditional systems are disappearing, and lands are abandoned (Hopkins and Holz 2006). Climate change, world population growth, and uncertainties over energy and water call for more focused research.

Land use conversion has depleted the terrestrial ecosystem C stock with major loss of the vegetation and soil C stock (Lal 2018; Lorenz and Lal 2018). Conversion to a restorative land use and adoption of good management practices may create a positive soil/ecosystem C budget that can lead to improved C sequestration rates in pastures, permanent crops, and lawns, and resulting from the restoration of soils prone to water erosion, also operated with grasslands. The adoption of best management practices—continuous ground cover, complex rotations, integrated nutrient management and no soil disturbance—can protect the soil organic carbon (SOC) stock and enhance ecosystem services (Lal 2018). Bai and Cotrufo (2022) reported that grasslands store near one-third of the global terrestrial C stocks, can act as an important soil carbon sink, with plant diversity increasing SOC storage.

Improved grazing management and biodiversity can provide C gains in global grasslands. Zhao et al. (2017) indicated that temperature, grazing intensity, and water availability are the major factors influencing SOC in grasslands of Inner Mongolia, China, while temperature and soil pH are more influencing in Mongolia, where grassland C sequestration is higher. Soussana et al. (2010) stated that soil carbon sequestration is the mechanism responsible for most of the greenhouse gas (GHG) mitigation potential in the agriculture sector and that grassland C sequestration has a strong potential to contribute for mitigating the GHG balance of ruminant production systems. However, CH_4 and N_2O emissions from livestock sector needs to be reduced and current SOC stocks preserved. More recently, Viglizzo et al. (2019) stated that grasslands sequester more carbon than forests because they are less sensitive to water stress and wildfires. This resilience of grasslands helps to preserve sequestered terrestrial C and prevent it from returning the atmosphere. The UN Decade on Ecosystem Restoration does not encourage afforestation of remaining semi-natural grassland and savannah ecosystems (Dudley et al. 2020) but proposes adopting a set of properly planned ecological, cultural, and social approaches for successful grassland and savannah restoration.

Enhancing biodiversity implies a good identification of grassland specialist species and of causes for favoring alien species richness. Noda et al. (2022) report that mowing is effective for the conservation of grassland specialists' diversity, but it is required to pay attention to the invasion of alien species from adjacent areas. Biodiversity in rangelands is decreasing due to the intensification of their use for production (Alkemade et al. 2013). Extensively managed grasslands are recognized globally for their high biodiversity and their social and cultural values (Bengtsson et al. 2019). These authors propose that "ecosystem service and food security research and policy should give higher priority to understand how grasslands can be managed for fodder and meat production alongside other ecosystem service". Texeira et al. (2015) reported that C gains are a key aspect of ecosystem functioning. In the Pampa biome, more than 80% of the species recorded by 1930 are still present, but the number of exotics has seven-fold increased (Burkart et al. 2011). In that case, the water availability was the main driving factor of floristic heterogeneity.

The brief review above definitely shows the importance of the grassland ecosystems at the world scale, as well as the importance of management for grassland to achieve improved production and ecosystem services, particularly C sequestration and biodiversity, and to mitigate and adapt to climate change. Grasslands management require knowledge of evapotranspiration (ET) as a main component of the water balance and as the driving force of plants transpiration and growth. Thus, considering the good number of published ET studies, it has been possible to perform a review aimed at extending the tabulated values of FAO56 (Allen et al. 1998), hence focusing on various types of grasslands, semi-natural ecosystems, and grasses. The review focused on the crop coefficient as defined by the FAO56 method (Allen et al. 1998), where vegetation (crop) ET (ET_c) is computed as $ET_c = K_c\ ET_o$, product of the reference ET (ET_o), also known as potential ET (PET, assumed equal to ET_o), by the specific (vegetation) crop coefficient (K_c). Thus, the articles published after 1998 were targeted. The FAO56 method (Allen et al. 1998) was the most often used in the papers reviewed, is the most common and easy method used for the generality of agricultural crops in the field practice, and their K_c are tabulated in FAO56. For these reasons, and as an opportunity to update and expand the Tables in FAO56, the FAO method was selected for the current review.

Nevertheless, other approaches to compute ET_c were adopted in the reviewed studies, which also computed ET_o and actual ($ET_{c\ act}$), thus allowing to obtain $K_{c\ act} = ET_{c\ act}/ET_o$. Therefore, the current paper shows the tabulated values of $K_{c\ act}$ for irrigated and non-irrigated grasslands, meadows, and pastures, for semi-natural vegetation consisting of steppes, savannas and other ecosystems, and tabulated $K_{c\ act}$ values for grasses, with distinction of their use for animal production or for landscape, presented in Sections "Semi-natural and planted grasslands", "Semi-natural grassland ecosystems" and "Grasses for hay, grazing and landscape", respectively. The analysis of the tabulated $K_{c\ act}$ allowed to derive standard transferable K_c values for the considered grassland ecosystems and grasses, which are presented in Section "Standard crop coefficients". Therefore, the current review consists of a full update and extension of standard K_c values proposed in the FAO56 guidelines for computing crop evapotranspiration aimed at supporting improved field and water management of grasslands, and more accurate water balances and hydrologic studies, thus easing the consideration of water balances in studies relative to ecosystem services where water plays a role.

Materials and methods

The review aimed at collecting the available $K_{c\ act}$ for grasslands and was performed through the widest possible search focused on papers reporting on actual K_c obtained from field measurements of grasses and grasslands actual evapotranspiration ($ET_{c\ act}$).

The search was performed in Science Direct and through the on-line pages of various journals, as well as using the bibliography lists of selected articles. Several languages were considered: English, Spanish, Portuguese, French, Italian, and German. In addition to the keywords evapotranspiration and crop coefficients, numerous other keywords were used including grass, semi-natural grasslands, planted grasslands, pastures, meadows, rangelands, steppe, savanna, prairie, shrubland, pampas, chaparral, and *páramos*. Only full articles were reviewed.

The criteria used for the selection of the papers from where single and basal $K_{c\ act}$ values were collected consist of the following:

(1) The papers should be of good/acceptable quality, without preference of journals where published.
(2) The $K_{c\ act}$ values should have been derived from adequate field research, exceptionally from solid review papers.
(3) The field methods should be well described and readable by any interested reader, and should refer to consistent methodologies that provide for computing the $ET_{c\ act}$, including when less common empirical field methods were used.
(4) The grass reference ET_o should be computed with full daily data sets using the FAO Penman Monteith equation (FAO-PM-ET_o). When a different equation was used, including when data sets with missing variables were available, either the ratio of the equation used to the FAO-PM-ET_o was commonly known, or information was available from the authors; a conversion factor of 1.15 was used when the ASCE-PM ET_r equation for alfalfa (Allen et al. 2006) or the Penman equation (Doorenbos and Pruitt 1977) were adopted.
(5) Under the conditions referred before, the $K_{c\ act}$ values were provided by the authors in Tables, graphics or in the text; for a few cases, when only $ET_{c\ act}$ and ET_o were provided, $K_{c\ act}$ (average) values were computed. Otherwise, data could not be considered.
(6) Another important aspect was relative to the description of the studied grassland; when information was too brief the paper was excluded; nevertheless, depending upon the rarity of the crop's information, data from papers where that information was less good, namely on botanical data, were used.
(7) In addition, the field and computation methods should be sufficiently descriptive, in line with the recommendations by Allen et al. (2011), to understand if the reported methods provided for reliable $ET_{c\ act}$ data. Otherwise, the study was not considered.

Among research studies on grasslands ET, many did not use the FAO56 method but, as for the generality of other methods, required specific field procedures. Field research methods included: the soil–water balance (SWB) based on observations of the soil water content (SWC) using soil sampling and various types of sensors; the field or catchment hydrologic water balance (HWB); the Bowen ratio energy balance (BREB); the eddy covariance system (EC); weighing and drainage lysimeters (WL and DL); mini or micro lysimeters (ML) to assess soil evaporation; and diverse but consistent empirical methods such as testing different K_c values against observed yields. Most field methods are described and 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 (Montheith 1965; PM), the Priestley-Taylor equation (Priestley and Taylor 1972; PT), and the double source method of Shuttleworth and Wallace (Shuttleworth and Wallace 1985; SW). The PM, the PT and the SW equations require specific field methods different from the SWB. Several studies were performed with support of properly calibrated models. The most used software models comprise SIMDualKc (Rosa et al. 2012; Pereira et al. 2020) and HYDRUS (Šimůnek et al. 2016). In addition, remote sensing (RS) was largely used mainly in the last decade. Both surface energy balance models such as METRIC, SEBAL, and SEBS (Allen et al. 2007), and RS vegetation indices such as NDVI (Glenn et al. 2011; Pôças et al. 2020), were adopted. A list of symbols, acronyms and abbreviations is included in Appendix B.

The tables for grasslands $K_{c\ act}$ were divided into three main groups with each one divided again according to the types of grasslands, and where the reviewed papers are "grouped" following the ecosystems type and/or farm use:

1. Semi-natural and planted grasslands and meadows, divided into semi-natural, non-irrigated and irrigated,
2. Semi-natural grassland ecosystems, comprising savannas, steppes, and other semi-natural ecosystems such as mixed forests and shrublands, and
3. Grasses for hay, for grazing and for landscape uses.

The tables provide information on the location of the studied sites, the authors, and the main grasses and the actual crop coefficients, and the conditions corresponding to the determination of the presented actual K_c values for the initial, mid-season and end season ($K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ respectively, Fig. 1), following the FAO56 definitions (Allen et al. 1998). The information provided aims at easing the transferability of K_c values, including when users consult the original papers.

Information on climate, the methods used for determining ET_o and $ET_{c\ act}$, the management adopted, the growing season and water supply are given in Appendix A, complementing data in Tables 1, 2, and 3.

The selected papers designate grasses, shrubs, and trees with the scientific or the common names. In this review paper, the scientific names are used. To ease recognizing the plants, a Table in Appendix C lists the scientific names used and the corresponding common name when known.

The tabulated actual K_c values are not adjusted to climate (Allen et al. 1998) because grasslands very often have a small height, thus small variation of K_c with wind speed and

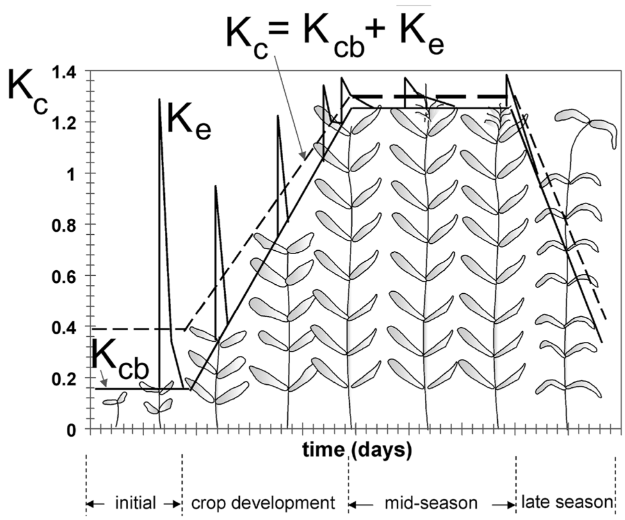

Fig. 1 Typical K_c/K_{cb} curves for a grassland used for grazing or seed (FAO56, Allen et al. 1998)

relative humidity. In addition, users generally know well that the transferability of K_c information is related to the type of grassland and the environmental conditions and, therefore, they are able to well transfer the tabulated values adopting small empirical corrections to K_c, of 5–10%, which values may slightly increase K_c in dry and windy conditions, and lower K_c in humid and calm environments as recommended in FAO56 (Allen et al. 1998).

The dual K_c approach proposed in FAO56 (Fig. 1a) was used by a few authors who reported basal crop coefficients (K_{cb}) representing the transpiration (T_c) component of ET, i.e., $K_{cb} = T_c/ET_o$ (Allen et al. 1998; Pereira et al. 2020). The actual K_{cb} values are tabulated together with the single $K_{c\ act}$ but using a bold and italic format of the characters. Since grasslands typically have a large density of plants well shading the ground, it results in a small soil evaporation (Paredes et al. 2018) and quite small differences to the single K_c, thus concluding that information on single averaged K_c is definitely sufficient for further assessment of water use and water balance.

Seminatural and planted grasslands

This section refers to actual K_c for the various types of grasslands that are used for animal feeding through grazing and hay, or to produce grass seed. The generic grasslands name is used. The first group of grasslands consist of the irrigated and non-irrigated grasslands, the latter being the most common ones, that include numerous semi-natural grasslands, which water supply is precipitation or, less often, high groundwater tables.

Semi-natural and planted non-irrigated grasslands

Table 1 shows $K_{c\ act}$ for semi-natural grasslands, meadows, and pastures in high elevation sites with identification of the field study location, reference of selected articles, the floristic composition, and conditions relative to the crop when the $K_{c\ act}$ were derived. Semi-natural grasslands occur in various cold and temperate climate ecosystems, as meadows in high elevation mountains of the Qilian Mountains and the Tibetan Plateau, the Andean *páramos* of the Equator, or the Alpine pasture of the Aosta Valley (Table 1).

The highland sites show large $K_{c\ act}$ values, around 1.0, for the summer, unfreeze period, similar to the high elevation grasslands reported in Section "Semi-natural and planted non-irrigated grasslands". Those high values mean that soil water was well available for satisfaction of the vegetation after the winter snow and ice melting. The period of grass growth has both high water and energy availability, however, with growth limited by the temperature. In high mountain and plateau locations, the winter is long and freezing, so reducing the mid-season and conditions for killing frost exist causing that the end-season may be anticipated. They are located far from farms and the rural population. The high elevation grasslands are generally semi-natural, whose reported grasses are rarely planted (not included in the Tables for grasses in Section "Grasses for hay, grazing and landscape").

Table 2 reports $K_{c\ act}$ for low mountain and lowland grasslands, where the crop season is longer, the winter is less cold and grasslands are located not far from farms, thus where human interventions have occurred, altering the flora by planting more productive grasses, and using fertilizers and pesticides, and adopting other management practices, like cutting for hay, not usual in semi-natural grasslands. The low mountain non-irrigated grasslands may be semi-natural, but those in low land are very often planted. The abandonment or mismanagement of the semi-natural grasslands also cause alterations due to the progressive invasion of shrubs and trees, which compete with grasses for water, nutrients, and energy.

The reported values (Table 1) show that $K_{c\ act\ ini}$ range 0.25 to 0.65, corresponding to the regrowth of grasses in spring, that depends upon the soil water availability by then. They are much lower than the $K_{c\ act\ mid}$, which ranges from 0.85 to 1.20; there are, however, lower mid-season values when water is much insufficient. $K_{c\ act\ end}$ values may be quite lower than $K_{c\ mid}$ when solar radiation progressively decreases, then followed by the decrease and end of growth, particularly for higher latitudes, and cold time installs. End season values may be close to the mid-season when growth stops abruptly due to sudden changes of temperature and radiation in the Fall due to killing frost occurrence. This

Table 1 Field derived actual crop coefficients ($K_{c\ act}$) for semi-natural high mountain grasslands and meadows for grazing and hay, with identification of the study sites, article reference, and main grasses

Identification	Reference	Main grasses	Actual crop coefficient derived from field observations				
			Conditions	$K_{c\ act\ avg}$	$K_{c\ act\ ini}$	$K_{c\ act\ mid}$	$K_{c\ act\ end}$
Alpine pasture at Torgnon, Aosta Valley, Italy	Corbari et al. (2017)	*Nardus stricta, Festuca nigrescens, Arnica montana, Carex* spp.				0.85	0.45
Mountain grasslands of Aosta Alps, Italy	Gisolo et al. (2022)	n/r		0.70			
Alpine grasslands in Canton of Valais, Switzerland	Smith et al. (2012)	Grasses from multiple sites at various elevations	Short season	0.95			
			Long season	0.88			
Andean Zhurucay páramo, Cajas Massif, Southern Ecuador	Carrillo-Rojas et al. (2019)	Tussock grasses *Calamagrostis* spp.	Wet period	0.93			
			Non-wet period	0.87			
High elevation Andean páramos, Machangara, southern Ecuador	Buytaert et al. (2006)	n/r	Natural vegetation, high slope	0.42			
			Planted grass, gentle slope	0.92			
Humid alpine meadow, Haibei, Qinghai-Tibetan Plateau, China	Dai et al. (2021)	*Kobresia* sp., and *Poaceae*	May–Sep	1.01	0.65	1.20	1.05
Subalpine meadows, Heihe River basin, Qilian Mountains, China	Gao et al. (2019)	*Elymus nutans, Foeniculum vulgare*	May–Oct	0.81	0.45	1.05	0.25
High mountain meadow, Yeniugou, Qilian Mountains, China	Yang et al. (2013)	*Kobresia capillifolia, Carex moorcroftii*	Summer	0.86			
Alpine meadow, Qilian Mountains Heihe basin, China	Yang et al. (2017)	*Kobresia capillifolia, Carex moorcroftii*	Unfrozen	0.82	0.25	1.20	0.40
			Frozen	0.19			
Alpine meadow of the Tibetan Plateau, China	Chang et al. (2017)	n/r			0.50	0.95	0.85
Humid meadow at Fenghuoshan, Qinghai-Tibetan Plateau, China	Li and Wang (2015)	*Stipa aliena, Kobresia tibetica, Festuca* spp., *Carex atrofusca*		0.55	0.30	0.85	0.40
Alpine meadow, Qinghai-Tibetan Plateau, China	Li et al. (2013)	*Kobresia humilis, K. pygmaea, K. tibetica, Stipa aliena*	Growing season (May–Sep)	1.00	0.65	1.20	n/r
			Non-growing	0.34			
Global ecosystem ET/ET_o, Global FluxNet	Liu et al. (2017)	n/r	World average of multiple sites		0.45	0.86	0.41

Symbols, abbreviations and acronyms are given in Appendix B

condition is not likely to occur in less elevation grasslands (Table 1).

The $K_{c\ act\ mid}$ tend to be higher where water is available, either due to rainfall or, in altitude, due to snow and ice melt; lower values refer to the grasslands in plateau steppes (e.g., Xilin, Zhao et al. 2010), where water availability is scarce. For the cases where only an average $K_{c\ act}$ value is reported, it may be observed that higher actual $K_{c\ avg}$ correspond to conditions similar to high $K_{c\ act\ mid}$. Overall, small values are for grasslands in dry areas.

Selected main characteristics of the grasslands description, namely the crop season period, water supply (precipitation and/or groundwater (GW)) and the methods used for determination of ET_o and $ET_{c\ act}$, are provided in Appendix A, in Tables 12 and 13, in correspondence to the Tables 1 and 2. Analyzing the variability of $K_{c\ act}$ values, it was found that those data are important to identify the type of grasslands and the quality of field and lab research work behind the reported $K_{c\ act}$, but do not help to explain their variability.

Table 2 Field derived actual crop coefficients ($K_{c\ act}$ and $K_{cb\ act}$) for non-irrigated grasslands and meadows in highland plateau and prairies

Identification	Reference	Main grasses	Actual crop coefficient derived from field observations				
			Conditions	$K_{c\ act\ avg}$	$K_{c\ act\ ini}$	$K_{c\ act\ mid}$	$K_{c\ act\ end}$
GW fed Pasture in Horqin Sandy Land, Inner Mongolia, China	Wu et al. (2016)	*Leymus chinensis*	Avg 2 sites: K_{cb}		***0.30***	***0.70***	***0.40***
			K_c		0.50	0.75	0.60
Grasslands of Xilin, Inner Mongolia, China	Zhao et al. (2010)	*Leymus chinensis* *Stipa grandis*	Ungrazed-1979		0.24	0.40	0.31
			Ungrazed 1999		0.23	0.38	0.33
			Moderate grazed		0.22	0.35	0.35
			Heavy grazed		0.20	0.30	0.28
			Grassland		0.45	0.86	0.41
Grassland at Zhanggutai, Liaoning, China	Zheng et al. (2012)	n/r	Grassland		0.15	0.89	0.65
Chippewa prairie grasslands, West-Central Minnesota, USA	Baeumler et al. (2019)	*Alisma* spp., *Carex* spp., *Cirsium* spp., *Dichanthelium* spp.	Previous burn		0.75	0.90	0.40
			Recent burn		0.71	0.80	0.35
Perennial pastures, Central Valley of California + Carson Valley of Nevada, USA	Howes et al. (2015)	n/r	Avg. 2 fields		0.72	0.90	
			Rainy season	0.71			
			Dry season	0.10			
Gudmundsen Sand Hills meadow, Nebraska, USA	Healey et al. (2011)	*Elymus smithii, Bouteloua gracili, Poa pratensis*	Growing season		0.54	0.90	0.55
Tallgrass prairie at Stillwater, Oklahoma, USA	Krueger et al. (2021)	*Schizachyrium scoparium, Andropogon gerardii, Sorghastrum nutans*	K_{cb}		***0.17***	***0.86***	***0.17***
			K_c		0.22	0.96	0.22
Pastureland at Hillsborough County, Central Florida, USA	Nachabe et al. (2005)	n/r			0.40	0.70	0.50
Pasture at Floral City, Central Florida, USA	Sumner and Jacobs (2005)	*Paspalum notatum*	2 years mean		0.59	0.95	0.45
Grassland in North Dakota, USA	Niaghi and Jia (2017)	n/r	2 years mean	0.80			
Meadow and grasslands in northern New York State, USA	Hwang et al. (2020)	*Phalaris arundinacea*	Meadow, Reed canary grass		0.96	1.19	
					0.98	1.32	
			Reed canary grass		1.05	1.23	
Intensively grazed pasture at Waikato, New Zealand	Pronger et al. (2016)	*Lolium perenne, Trifolium repens*			1.05	1.05	1.05
Wet grasslands in Upper Pangani River Basin, Tanzania	Kiptala et al. (2013)	n/r	Wet season	0.60			
			Dry sesaon	0.20			
Mountain semi-natural pastures at Montalegre, northern Portugal	Pôças et al. (2013)	*Cytisus* spp., *Erica* spp., *Festuca rubra, Agrostis* spp., *Nardus stricta*	Grazing	0.65			

Table 2 (continued)

Identification	Reference	Main grasses	Actual crop coefficient derived from field observations					
			Conditions		$K_{c\ act\ avg}$	$K_{c\ act\ ini}$	$K_{c\ act\ mid}$	$K_{c\ act\ end}$
Pasture at Ribeirinha, Terceira Island, Azores, Portugal	Fontes et al. (2004)	*Lolium perenne* *Trifolium repens*	Year average Grazing and hay		1.02			
Grasslands at Havelländisches Luch (HL)and Spreewald Wetland (SW), eastern Germany	Dietrich et al. (2021)	n/r	HL, Wet year		1.09	0.90	1.10	1.00
			Dry year		0.85			
			SW, Wet year		0.95	0.75	0.95	0.80
			Dry year		0.81			
Grassland at Rollesbroich, Lower Rhine Valley, Germany	Groh et al. (2015)	*Lolium perenne, Cynosurus cristatus*	1st cut			0.75	1.25	1.50
			2nd cut			0.40	1.05	1.20
			3rd cut			0.50	1.25	1.40
			4th cut			0.40	1.20	1.25
			Grazing			0.50	1.00	1.00
Mountain pasture sward in the Western Carpathians, Poland	Kuźniar et al. (2011)	*Lolium perenne, Cynosurus cristatus*	Grazing		0.75			
Meadows in Poland	Kasperska-Wołowicz and Łabędzki (2006)	n/r	High yield	1st cut		0.50	1.20	1.30
				2nd cut		0.55	1.30	1.35
			Median yield	1st cut		0.45	1.10	1.30
				2nd cut		0.45	1.15	1.25
Pastures and meadows in North-East Poland	Szejba (2011)	n/r	Pasture			0.70	0.89	n/r
			Meadow 1st cut			0.96	1.22	1.24
			2nd cut			0.80	1.16	1.20
Grass near Fenéka pond, Hungary	Anda et al. (2015)	*Festuca* spp.				0.90	1.10	n/r

Symbols, abbreviations and acronyms are given in Appendix B

Bold italics are to highligh that these values are K_{cb} which differ from the other values which are K_c

Irrigated grasslands

Irrigated grasslands are commonly located in lowland areas or in low slope fields, generally of low altitude, and are planted for grazing or for hay. The information on sites and $K_{c\ act}$ and $K_{cb\ act}$ values are reported in Table 3, while data further characterizing the irrigated grasslands are shown in Appendix (Table 14).

When grasslands are cropped for hay, their $K_{c\ act}$ values refer to the observed cycles of grass cutting or to an average or representative cycle according to decision criteria of authors. Each cycle is described by the common FAO K_c curve (Fig. 1) comprising four crop coefficient stages—initial, development, mid-season, and late season stages—as presented in Fig. 2 for a case with four cycles. Thus, each cycle is characterized by a $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$. The $K_{c\ ini}$ corresponds to the K_c that follows the cut, while $K_{c\ end}$ refers to the K_c when the cut is performed, the $K_{c\ cut}$. Grass height h and cover fraction f_c may use the same subscripts as for K_c.

In rotary grazing, similarly, there are various cycles comprising a period when the livestock is grazing followed by a period of grass development until animals start grazing again. Only two K_c are necessary for fully describing these cycles, the $K_{c\ high}$ when the animals enter in the grass field, and $K_{c\ low}$ when they end grazing. For turf grass in any landscape grass is mowed to the height h_{low} when it attains the height h_{max}. Researchers, however, do not yet adopt a standardized nomenclature, which may result in confusing. This nomenclature is used in the Tables presented in this article.

Table 3 shows that, with a single exception, the reported $K_{c\ act\ avg}$ and the $K_{c\ act\ mid}$ for irrigated grasslands are close to 1.0 with values ranging between 0.80 and 1.20. These values are higher than for non-irrigated grasslands (Tables 1 and 2) because there is more water available due to irrigation and, likely, the grasses' soils are often

Table 3 Field derived actual single and basal crop coefficients ($K_{c\ act}$ and $K_{cb\ act}$) for irrigated grasslands, meadows, and pastures

Identification	Reference	Main grasses	Management f_c and h (m)	Actual crop coefficient derived from field observations				
				Conditions	$K_{c\ act\ avg}$	$K_{c\ act\ ini}$	$K_{c\ act\ mid}$	$K_{c\ act\ end}$
Pasture in Gareh Bygone Plain, South of Zagros, Shiraz, Iran	Pakparvar et al. (2014)	*Helianthemum lippii, Artemisia sieberi, Aegilops cerasa, Medicago polymorpha*	Grazing	Average	0.47	0.42	0.55	0.55
				Peak by Jan-Feb			1.00	
Dairy pastures in Goulburn-Murray District, Victoria, Australia	Abuzar et al. (2017)	n/r	Grazing	Top 5% NDVI	0.85			
Irrigated pasture, Murray-Darling Basin, Australia	Bethune and Wang (2004)	*Trifolium repens, Lolium perenne Paspalum* spp.	Grazing f_c=0.97	Annual average.	1.05	0.80	1.04	0.80
Irrigated grasses at Kyabram, northern Victoria, Australia	Greenwood et al. (2009)	*Lollium multiflorum* *Trifolium repens, T. resupinatum* *T. subterraneum Festuca rundinácea, Medicago sativa*	f_c=0.97	Ryegrass + white clover	***K_{cb}***	***0.70***	***1.20***	
				Tall fescue +w. clover		***0.90***	***1.20***	
				Alfalfa		***0.25***	***1.20***	
				Persian clover + Italian ryegrass		***0.80***	***1.10***	
				Subterranean clover + Italian ryegrass		***1.00***	***1.15***	
Irrigated pasture in northern Victoria, Australia	Qassim et al. (2008)	*Lolium perenne, Trifolium* spp., *Paspalum dilatatum*	Grazing	Spring-summer	1.04			
				Winter	0.96			
Pastures at New England University, New South Wales, Australia	Alam et al. (2018)	*Festuca arundinacea*	Mowing h_{low}=0.05	2 weeks after mowing		0.30	0.50	
				3 weeks after mowing			0.85	
Grazing pastures, Christchurch, New Zealand	KC et al. (2018)	*Lolium perenne*	Rotational grazing h = 0.05–0.30	Height 5 cm	0.50			
				10 cm	0.60			
				20 cm	0.80			
				30 cm	1.00			
Meadows in mountain areas, Montalegre, Portugal	Pôças et al. (2013)	*Holcus lanatus, Plantago lanceolata, Dactylis glomerata, Festuca* spp.	Hay and grazing		0.88			
Pastures at Terra Chã, Galize, Spain	Cancela et al. (2006)	*Lolium perenne, Trifolium repens*	Grazing and cuts for hay	1st cut cycle		0.55	1.05	0.55
				2nd cut cycle		0.55	1.05	0.55
				3rd cut cycle		0.55	0.80	0.55
				Grazing		0.55	0.90	
Irrigated grasses at Piracicaba, São Paulo, Brazil	Sanches et al. (2019)	*Megathyrsus maximus* cv. 'Mombaça'	7cut cycles	Fall-Winter	1.09			
			6 cycles	Spring-Summ	0.99			
		Idem, + *Avena strigosa* + *Lollium* spp.	5 cycles	Fall-Winter	0.96			
		Cynodon dactylon	6 cycles	Fall-Winter	0.93			
			7 cycles	Spring-Summ	1.00			
		Idem, + *Avena strigosa* + *Lollium* spp.	5 cycles	Fall-Winter	1.02			

Table 3 (continued)

Identification	Reference	Main grasses	Management f_c and h (m)	Actual crop coefficient derived from field observations				
				Conditions	$K_{c\ act\ avg}$	$K_{c\ act\ ini}$	$K_{c\ act\ mid}$	$K_{c\ act\ end}$
'Marandú' palisade-grass single (S) and combined (C) in Piracicaba, Brazil	Souza et al. (2021)	*Brachiaria brizantha* cv."Marandu", *Avena strigosa, Lolium multiflorum*	Grazing	(S), year		0.62	0.95	n/r
				(C), Aut-Win		0.67	0.80	0.50
				(C), Spg-Sum		0.50	0.90	0.83
Pasture at Twitchell Island, Sacramento River, CA, USA	Snyder et al. (2008)	*Lollium* spp., *Festuca arundinacea, Cynodon dactylon*	Grazing h_{cut} = 0.10–0.20	Apr–Sep	0.98			
Pasture at Campbell Tract, Davis, CA, USA	Snyder et al. (2008)	*Festuca arundinacea, Trifolium* sp.	Mowing h_{cut}=0.08–0.12	Apr–Sep	1.00			
Bahiagrass at Citra, Central Florida, USA	Jia et al. (2009)	*Paspalum notatum*	Grazing		0.64	0.35	0.77	0.35
Permanent pastures in Imperial Valley, USA	Allen et al. (2005a)	n/r	Grazing f_c=1.0	***K_{cb}***		***0.35***	***0.85***	***0.70***

Symbols, abbreviations and acronyms are given in Appendix B

Bold italics are to highligh that these values are K_{cb} which differ from the other values which are K_c

of better quality and management of nutrients are more careful. An exception refers to a deficit irrigation site in the arid Gareh Bigorn Plain, southern Iran (Pakparvar et al. 2014). The reported ground cover fraction is always high, i.e., f_c = 1.0, which indicates that grasslands were well managed. Most of the cases in Table 3 report average information; only one case refers 3 cycles cutting for hay.

Two cases report $K_{cb\ act}$ values, one with $K_{cb\ act\ mid}$ lower than $K_{cb\ act\ ini}$ and $K_{cb\ act\ end}$ because the site is dry and hot (Imperial Valley, California, Allen et al. 2005a), thus affecting plant growth, so with higher values when weather is mild. The other (in Victoria, Australia, Greenwood et al. 2009) reports experimental $K_{cb\ act}$ results that correspond to good plant growth, thus to high $K_{cb\ act}$.

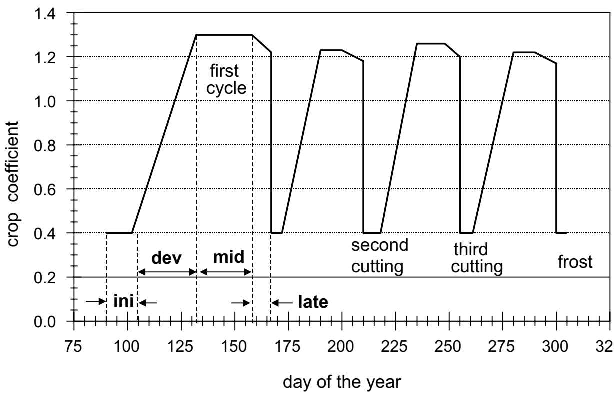

Fig. 2 Typical K_c/K_{cb} curves for a grassland cropped for hay with multiple cutting cycles (FAO56, Allen et al. 1998)

Semi-natural grassland ecosystems

Semi-natural savanna and steppe type grasslands

Both savanna and steppe designations, herein, do not refer to specific biomes but include a variety of other biome like *cerrado* and *catinga* in Brazil, *dehesa* or *montado* in the Iberian Peninsula, or to grasslands in open forests. Naturally, the grasslands included under those designations vary much with climate and, regionally, with the dominant species and environment, particularly with soils. Various savanna-type semi-natural grasslands are reported in Table 4. Despite these grasslands are used for grazing after long time, the grasses and shrubs are different from those in the planted grasslands and of the domesticated grasses reported in Section "Grasses for hay, grazing and landscape" hereafter. Because savanna grasslands are not irrigated, both $K_{c\ act\ mid}$ and $K_{c\ act\ avg}$ show a seasonal effect related with the precipitation regime, with higher $K_{c\ act}$ in the rainy seasons, not when more solar energy is available, i.e., contrarily to reported grasslands in the preceding section, savannas are mostly water limited and less energy limited. The case of the oak savanna (montado) of Évora (Paço et al. 2009), showing very low $K_{c\ act}$ due to severe drought, is a good example. A unique example of effects of savanna conservation is provided by Descheemaeker et al. (2009, 2011), where grazed and protected savanna show different $K_{c\ act\ mid}$ values, higher in the latter case due to better growth of the vegetation.

In case of steppe (Table 5), there are similar behaviors, as for the high plateau steppe in Inner Mongolia reported

Table 4 Field derived actual crop coefficients ($K_{c\ act}$) for semi-natural savanna-type grasslands

Identification and location	Reference	Dominant species	Climate	Methods for estimating ET_o and $ET_{c\ act}$	Actual crop coefficient derived from field observations				
					Conditions	$K_{c\ act\ avg}$	$K_{c\ act\ ini}$	$K_{c\ act\ mid}$	$K_{c\ act\ end}$
Cerrado grassland at Águas de S. Bárbara, S. Paulo, Brazil	Silva et al. (2018)	n/r	Tropical subhumid, dry winter	FAO56-ET_o RS-SEBAL and SAFER + NDVI	After large rains	1.21			
					After dry periods	1.06			
					After large rains	0.88			
					After dry periods	0.59			
Semiarid savanna in highlands of Tigray, Ethiopia at (1) May Ba'ati (forest), (2) Kunale (3) Adewro	Descheema-eker et al. (2009)	Closure: 0 years			Degraded grazing			0.28	
		5 years			Restored land			0.67	
		10 years						0.78	
		20 years						0.96	
		25 years						1.04	
	Descheema-eker et al. (2011)	Forest: *Acacia etbaica, Carissa edulis, Dodonaea rotundifolia* Grasses: n/r	Semiarid tropical, rain in summer	FAO56-ET_o BUDGET model SWC-grav.	(1) Church forest			1.07	
					Old protected land			1.04	
					Grazing land			0.62	
					(2) Recent prot. Land			0.73	
					Old protected land			1.03	
					Grazing land			0.74	
					(3) Recent prot. Land Grazing land			0.90 1.02	
Woodland savanna in North Kordofan state, Sudan	Abaker et al. (2018)	*Acacia senegal* and n/r grasses (short time $K_{c\ mid}$)	Semiarid tropical,	J-H ET_o WATBAL model SWC-grav.	El Demokeya: grass	0.20		0.70	
					Acacia +grass	0.30		1.00	
					El Hemaira: grass	0.25		0.80	
					Acacia 15 y.+grass	0.35		1.30	
Mediterranean oak savanna (dehesa) at Caceres, Spain	Campos et al. (2013)	*Quercus* spp.	Med., mild winter, dry hot summer	FAO56-ET_o SWB, EC, RS-NDVI	Winter	0.90			
					Summer	0.35			
Mediterranean oak savanna (dehesa) at Sierra de Cardeña y Montoro, Spain	Carpintero et al. (2020)	*Quercus ilex, Q. faginea,* Ass. *Hordeum leporinum*	Med., mild winter, dry hot summer	FAO56-ET_o EC, SWB with K_{cb} from SAVI and f_c	Trees and grasses		0.15	0.80	0.15
Mediterranean oak savana (montado), (very heavily grazed) Évora, Portugal	Paço et al. (2009)	*Q. rotundifolia, Avena barbata, Vulpia bromoides, Ornithopus compressus*	Med., mild winter, dry hot summer	FAO56-PM ET_o SF, EC	***K_{cb}***			***0.21***	
					K_c			0.34	
Fragmented fields with semi-natural grass at Cascine, Florence, Italy	Pieri et al. (2019)	n/r	sub-humid Med.	J&H ET_o MODIS-NDVI, SWB-capacit.	Annual		0.60	1.20	0.60
Siberian plain grassland, Tyumen, Tyumen Oblast, Russia	Fleischer et al. (2015)	*Deschampsia cespitosa, Bromopsis inermis, Poa angustifolia*	Transition from cold forest to pre-taiga	Penman ET_o EC	Summer	0.54			

Symbols, abbreviations and acronyms are given in Appendix B

Bold italics are to highligh that these values are K_{cb} which differ from the other values which are K_c

Table 5 Field derived actual crop coefficients ($K_{c\ act}$) for semi-natural steppe grasslands

Identification and location	Reference	Dominant species	Climate	Methods for estimating ET_o and $ET_{c\ act}$	Actual crop coefficient derived from field observation				
					Conditions	$K_{c\ act\ avg}$	$K_{c\ act\ ini}$	$K_{c\ act\ mid}$	$K_{c\ act\ end}$
Sagebrush steppe at Monticello, SE Utah	Jarchow et al. (2022)	*Elymus smithii Artemisia tridentata*	Cold winter, mild summer	Classe A pan DL, RS-NDVI	Summer	0.40			
Desert steppe at Sunitezuo, Inner Mongolia, China	Zhang et al. (2012)	*Poa* spp. and dwarf shrub *Stipa klemenzii*	Arid, cold winter, warm summer	FAO56-ET_o	High peak K_c	0.15		0.75	
				EC	Low peak K_c	0.17		0.58	
Desert steppe at Xilinhot, Inner Mongolia, China	Hou et al. (2010a)	*Leymus chinensis, Stipa grandis, Artemisia frigida*	Semiarid, dry very cold winter	FAO56-ET_o SWB	Average of 4 locations, 2 year		0.30–0.45	0.85–1.00	0.50–0.70
Disturbed and undisturbed steppe at Duolun, Xilinhot, and Ordos, Inner Mongolia, China	Lu et al. (2011)	*Stipa krylovii, Artemisia frigida*	Semiarid, freezing winter, warm summer	FAO56-ET_o EC	Undisturbed steppe	0.64			
		Stipa grandis, Leymus chinensis			Disturbed steppe	0.36			
		S. grandis, A. frigida			Grazed steppe	0.44			
Duolon (D) and Xilinhot (X) steppes, Inner Mongolia, China	Miao et al. (2009)	(D): *S. krylovii, A. frigida, L. chinensis* (X): *L. chinensis, S. grandis, Achnatherum sibiricum*	Arid, freezing winter, warm summer	FAO56-ET_o EC, SWB-SWC reflect.	D: well managed		0.38	0.81	0.30
					X: fenced steppe		0.27	0.44	0.31
					X: degraded		0.30	0.40	0.30
Oasis-desert transition at Badain Jaran Desert and Zhangye Oasis, Middle Heihe river, China	Zhao and Zhao (2014)	*Haloxylon ammodendron, Suaeda glauca, Bassia dasyphylla*	Arid, dry winters and hot summer	FAO56-ET_o PM comb. eq.	Shrubs and grasses for dunes' control, spring-summer growth season		0.15	0.35	0.15
Steppe pastureland and Gobi Desert in western Mongolia	Batsuk et al. (2021)	Native vegetation in Gobi Desert	Cold and dry	FAO56-ET_o	Desert steppe	0.15–0.28			
		Grazed native vegetation		Soil cover and LAI with wide testing	Semi-arid steppe	0.25–0.80	0.10	0.95	0.10
Caatinga grassland, Petrolina, Brazil	Carvalho et al. (2018)	n/r	Tropical, hot semi-arid	FAO56-ET_o	Rainy season	0.58			
				Energy balance	Dry season	0.21			
Caatinga, São Francisco River, Petrolina, Brazil	Teixeira (2010)	n/r	Tropical, hot semi-arid	FAO56-ET_o	Rainy season	0.50			
				RS, EB, EC, PMeq	Dry season	0.20			

Symbols, abbreviations and acronyms are given in Appendix B

by Zhang et al. (2012), and for two Brazilian *catinga* studies (Teixeira 2010; Carvalho et al. 2018), all referring higher $K_{c\ act}$ values when it rains and the soil water availability increases. There are various cases where $K_{c\ act}$ for protected or well managed steppe grasslands is much higher than for commonly grazed steppes, e.g., Miao et al. (2009) and Lu et al. (2011) relative to the high plateau of Inner Mongolia. $K_{c\ act}$ results for steppe, like for savanna, indicate that related grasslands plant development is mainly water limited and less energy limited. This fact is important for management and relative to ecosystem services; therefore, in agreement with $K_{c\ act}$ results analyzed in the previous section, it allows to consider that water management of grasslands may have implication on various services, mainly biodiversity and carbon sequestration, since these services are better when plants grow favorably.

Semi-natural grasslands in cold and temperate ecosystems

The *pampa* grasslands, at a low altitude, show $K_{c\ act\ avg}$ near 0.85 without evident distinction between seasons, likely due to a more favorable precipitation regime. Semi-natural grasslands in low precipitation areas have a lower $K_{c\ act\ mid}$ or $K_{c\ act\ avg}$ than *pampa* sites and show the seasonal influence of the rainfall regime. It is important to note that main grasses in Table 6 are different from a site to another.

Semi-natural grasslands in mixed forests and shrublands

Grazing is common in open mixed forests where grasses are often native if management did not favor the loss of semi-natural grass vegetation in favor of alien species. Contrarily, in planted forests, it is common that the native/semi-native understory vegetation has changed after introducing the new tree species. It is, therefore, likely that grasslands growing as understory of mixed forests area are considered semi-natural.

Table 7 shows various sites where this condition could be accepted but which research papers may have not provided related full information. Data in Table 7 show that both dry and humid climates, e.g., Roupsard et al. (2006) and Corbari et al. (2017), have $K_{c\ act}$ varying seasonally in relation to water availability. In general, $K_{c\ act}$ of mixed forests varies in a small range, 0.45 to 0.60. Shrublands show higher $K_{c\ act}$ values than mixed forests, likely because shrub roots can explore the soil to a large depth and solar energy available to grass is less affected by shadow, so overall contributing to a higher actual K_c.

Grasses for hay, grazing and landscape

This Section "Grasses for hay, grazing and landscape" refers to domesticated grasses used in agricultural planted grasslands and in landscape and sport fields, which are described in Tables 8, 9 and 10. It may be noted that these domesticated grasses were rarely reported among the main grasses of semi-natural grasslands, in previous Tables 1, 2, 3, 4, 5, 6 and 7.

Grasses for hay are mainly legume-grasses that grow fast under favorable environmental conditions and that respond well to cuts and allow numerous cut cycles during a crop season as represented in Fig. 2. For most cases, tabulated actual $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ values describe the cut cycles; otherwise, only $K_{c\ act\ avg}$ was reported for one grass.

Alfalfa is the most common grass for hay and the most studied one, namely with four papers using the dual K_c approach (Table 8). Results are quite similar, with actual $K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$ of approximately 0.30, 1.15 and 1.10, respectively. The higher mid-season value, reported by Hunsaker et al. (2002), shows the effect of a dry, hot, and windy climate. The reported values, considering that alfalfa grass covers well the soil (f_c~1.0), result in $K_{c\ act}$ quite close to $K_{cb\ act}$, thus, actual $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ of 0.40, 1.20 and 1.15, respectively. These values are coherent when compared to the standard tabulated values in FAO56 (Allen et al. 1998) and consist of standard K_c.

Several grasses have $K_{cb\ act}$ values similar to those of alfalfa (Table 8). However, most of them show $K_{c\ act}$ values varying with the cuts due to seasonality effects, which relate with climate dryness or wetness and windy conditions, more important when the grass is high by the mid and end stages, as proposed in the FAO56 equation for correction with climate. This is typically the case for blue panic cropped at Jeddah, Saudi Arabia (Ismail and El-Nakhlawy 2018). To be also noted that end-season $K_{c\ act}$ maybe larger or equal then $K_{c\ act}$ at mid-season, despite it is commonly a little smaller for most cases. The reported value is only $K_{c\ avg}$ in case of palisade grass (Antoniel et al. 2016), which corresponds to a less accurate field measurement but quite useful to indicate that this grass (*Brachiaria brizantha*) likely is a high-water demanding crop. However, information in this Table 8 is more useful when users compare various grasses.

Table 9 refers to the field derived actual single and dual crop coefficients for grasses cropped for grazing and seed production. Often, only one K_c/K_{cb} curve is required. However, a precise management requires that specific curves (Fig. 2) are used in rotary grazing, when h_{low} and h_{cut} are well defined, or when the time interval between cuts is defined with the cumulative growth degree days (CGDD).

Table 6 Field derived actual crop coefficients (K_c) for semi-natural grasslands in temperate climates

Name	Reference	Dominant species	Climate	Methods for estimating ET_o and $ET_{c\ act}$	Actual crop coefficient derived from field observation				
					Conditions	$K_{c\ act\ avg}$	$K_{c\ act\ ini}$	$K_{c\ act\ mid}$	$K_{c\ act\ end}$
Grassland in Amplero plateau, Abbruzzo, Italy	Chiesi et al. (2018)	*Poa* spp., *Trifolium* spp. *Medicago* spp., *Geranium* spp. *Cerastium* spp.	Alpine-Med. humid	FAO56-PM ET_o Field tested K_c values	Growing season		0.70	1.00	0.70
Grazing pasture in Riggs Creek, Murray-Darling, Australia	Wu et al. (2021)	n/r	Semi-humid temperate	FAO56-PM ET_o	Summer	0.25			
				EC, PMeq.	Winter	0.22			
Arid Andean pasture, Mendoza, Argentina	Contreras et al. (2011)	n/r	Temperate, dry	FAO56-PM ET_o RS-EVI		0.44			
Native pasture, Gareh Bygone Plain, South of Zagros, Shiraz, Iran	Pakparvar et al. (2014)	*Helianthemum lippii, Artemisia sieberi, Aegilops cerasa, Medicago polymorpha*	Continental, dry and hot summer	FAO56-PM ET_o	Deficit irrigated		0.42	0.55	0.55
				SEBS energy balance	Rainfed		0.38	0.45	0.45
Grassland with salty GW, Hetao Plane, Inner Mongolia, China	Yang et al. (2012)	n/r	Very cold winter, very dry summer	FAO56-PM ET_o	Low WTD	0.47			
				SEBAL, regional SWB	High WTD	0.55			
Pampa grasslands at Entre Ríos, Central Argentina	Nosetto et al. (2012)	*Stipa* spp, *Bromus* spp, *Paspalum* spp, *Piptochaetium* spp	Temperate sub-humid	FAO56-PM ET_o RS-NDVI, SWB-grav. HYDRUS-1D	Pampa grasslands	0.59	0.45	0.70	0.50
Pampa pastureland in Rio Grande do Sul, Brazil, at: Santa Maria	Rubert et al. (2018)	*Andropogon lateralis, Axonopus affinis, Paspalum notatum, Aeristida laevis*	Temperate humid, hot summer	FAO56-PM ET_o Flux towers energy balance	Fall-Winter	0.82			
					Spring-Summer	0.82			
Pedras Altas		*A affinis, A laevis, P. notatum, Eriantus angustifolium*			Fall-Winter	0.82			
					Spring-Summer	0.98			

Symbols, abbreviations and acronyms are given in Appendix B

Table 7 Field derived actual crop coefficients ($K_{c\ act}$) for semi-natural grasslands in mixed forests and shrublands

Name	Reference	Dominant species	Climate	Methods for estimating ET_o and $ET_{c\ act}$	Crop coefficient derived from field observations				
					Conditions	$K_{c\ act\ avg}$	$K_{c\ act\ ini}$	$K_{c\ act\ mid}$	$K_{c\ act\ end}$
Chestnut Ridge, Oak Ridge, Tennessee, USA	Corbari et al. (2017)	*Quercus* spp.	Temperate climate	FAO56-PM ET_o	Winter	0.10			
				FLUXNET	Summer	0.60			
Duke Forest, Durham, North Carolina, USA		*Quercus* spp., *Carya* spp. trees	Temperate climate	FAO56-PM ET_o	Winter	0.10			
				FLUXNET	Summer	0.45			
Black Hills, Oak Ridge Lab., Tennessee, USA		Evergreen trees, *Pinus ponderosa*	Temperate climate	FAO56-PM ET_o	Winter	0.05			
				EC	Summer	0.19			
Tropical palm canopy, Espiritu Santo, Vanuatu, South Pacific	Roupsard et al. (2006)	*Cocos nucifera* (f_c=0.75, *h* = 16 m) with understory *Paspalum* sp., *Mimosa* sp.	Tropical climate	FAO56-PM ET_o EC and SF	Cool season	0.79			
					Warm season	0.59			
					Summer	0.19			
High water-table shrubs, Great Basin, Owens Valley, East Sierra Nevada, USA	Steinwand et al. (2001)	*Atriplex lentiformis, Chrysothamnus nauseosus Sarcobatus vermiculatus*	Dry, cold winter and hot summer	FAO56-PM ET_o Transpiration from stomatal conductance and LAI modelling	***K_{cb}***				
					Atriplex sp.		***0.10***	***0.40***	***0.10***
					Chrysothamnus sp.		***0.10***	***0.80***	***0.15***
					Sarcobatus sp. (Mar-Oct)		***0.10***	***0.70***	***0.10***
Mixed forest, Changbaishan, South Korea	Park et al. (2017)	*Pinus koraiensis*	Cold winter, mild rainy summer	FAO56-PM ET_o MODIS-NDVI, ECV-SM	n/r		0.20	0.80	0.20
Mongolica pines at Keerqin Sandy Land, Liaoning, China	Zheng et al. (2012)	*Pinus silvestris*, var. '*mongolica*'	Monsoon, cold winter, hot summer	FAO56-PM ET_o CROPWAT model	Mongolian pine		0.50	0.62	0.55
					Shrubland		0.15	0.89	0.65
					Grassland		0.12	0.82	0.63
Trees in hyper-arid sites, Ejina, Inner Mongolia, China	Hou et al. (2010b)	*Populus euphratica*	Hyper-arid, cold winter, hot summer	FAO56-PM ET_o BREB, SWC-TDR	Growing season (May–Sep)		0.40	0.55	0.23
Shrubland + poplar in Ordos, Inner Mongolia, China	Lu et al. (2011)	*Artemisia ordosica*	Arid, cold winter, hot summer	FAO56-PM ET_o	Shrubland	0.64			
		Populus sp.		EC	Poplar	0.77			
Pinus and *Fagus* forests in low and high lands, Italy	Chiesi et al. (2018)	*Pinus pinaster* and *Pinus pinea*	Med. subhumid	FAO56-PM ET_o	San Rossore: by the Arno River and Tyrhenian		0.60	0.70	0.60
		Fagus sylvatica	Mountain	Field tested K_c values	Collelongo, Abruzzo		0.20	0.70	0.20
Native trees in Gareh Bygone Plain, Shiraz, Iran	Pakparvar et al. (2014)	*Ziziphus nummularia* *Acacia victoria*	Continental dry and hot summer	FAO56-PM ET_o	Trees, dense		0.80	0.90	0.90
				SEBS energy balance	Trees, sparse		0.35	0.45	0.45
Native dry forests, Entre Ríos, Central Argentina	Nosetto et al. (2012)	Dry forests: *Prosopis* spp., *Geoffroea* spp., *Celtis* spp, *Acacia* spp.	Temperate sub-humid	FAO56-PM ET_o NDVI-MODIS, SWB-Hydrus	Native forests with grass	0.82	0.65	0.85	0.75
Worldwide Global ecosystem ET/ET_o	Liu et al. (2017)	Mixed forest	Various climates	FAO56-PM ET_o Global FLUXNET	Mixed forests		0.23	0.39	0.14

Symbols, abbreviations and acronyms are given in Appendix B

Bold italics are to highligh that these values are K_{cb} which differ from the other values which are K_c

The latter is shown through an example with Bermuda grass cv "Tifton 85" experimentally cropped in southern Brazil (Paredes et al. 2018). This case also shows that for small grazing time intervals there is no need to adopt grazing cycles (Fig. 2), but this becomes of interest when such intervals between successive grazing events are large and differences between crop heights and K_c are larger, e.g., if CGDD=372 °C is adopted (Paredes et al. 2018).

It may be advisable to adopt different K_c values for groundwater-fed grass, where $K_{c\ act}$ varies with the water table depth (WTD), e.g., the Timothy and Italian ryegrass cases referred by Mueller et al. (2005). Generally, $K_{c\ act\ mid}$ varies in the range 0.80 to 1.00 but $K_{c\ act\ ini}$ and $K_{c\ act\ end}$ values have a larger range of variation, which is likely due to management and to climate, mainly relative humidity of the air and wind speed. Grasses cropped for seed have smaller $K_{c\ act\ end}$ since they are harvested following senescence and maturation of the seeds.

The grasses used for landscape (Table 10) are those able to live healthy and fully covering the ground while being frequently or very frequently mowed to small (5–8 cm) or very small heights (< 1.5 cm) as used respectively for lawns and for golf courses. Generally, knowing a single $K_{c\ avg}$ is enough for a good irrigation, commonly in the range 0.60–0.80 for lawns and larger in case of golf greens because the requirements of quality are much larger for the latter.

The grass actual K_c values summarized in Tables 8, 9 and 10 concern grass fields with large f_c (> 0.95), and they are appropriate for computing ET for in hydrologic and water resources studies.

Standard crop coefficients

From the analysis above and taking into consideration the tabulated information (Tables 1, 2, 3, 4, 5, 6 and 7) and the related papers, it is possible to propose a set of standard K_c values for the referred grasslands. Nevertheless, the previously tabulated actual K_c values may be used as indicative values for management or planning, e.g., for use to estimate ET in irrigation scheduling tools or models applied only to similar grasslands, i.e., not generally transferable. Differently, the standard K_c values, to be tabulated in FAO56 and shown in the Table 11, are transferable for a wider use relative to the corresponding types of grasslands, i.e., in irrigation scheduling tools and models and in hydrologic or water resources studies and models. Particular attention must be given to the climate, comparing conditions in the original location, summarily indicated in the Tables, and in the location where the transferred K_c is to be used. The defined standard K_c values for semi-natural and planted grasslands and for grasses for animal feeding and landscape uses are presented in Table 11.

The proper use of standard values of grasslands implies that user knows that tabulated values refer to non-stressed or mild-stressed vegetation. Tables 1, 2, 3, 4, 5, 6 and 7 show that low $K_{c\ act}$ values occur often, particularly for semi-natural vegetation in dry climates, namely steppe and savanna ecosystems, where actual K_c may vary much. Thus, when wishing to transfer a K_c to a dry or a drought prone area it is advisable to pay attention to the tabulated actual K_c (Tables 1, 2, 3, 4, 5, 6 and 7). The same happens with the use of standard values of grasses (Tables 8, 9 and 10). Their tabulated values are generally non-stressed or mild stressed. It is our conviction that for both grasslands and grasses transferability is adequate if users analyze carefully all related Tables and, in addition to climate, also take into consideration the dominant species.

Conclusions

The current review presents to users a large information on crop coefficients for determining crop evapotranspiration and, thus, to support new approaches for management taking into consideration both production for animal feeding and ecosystem services. Moreover, the review has shown that a large fraction of the grasslands is semi-natural and, therefore, may help in fighting climate change if appropriately managed for conservation.

The first group of grasslands focused those that are being used for grazing or hay, planted or semi-natural, normally using mixed grasses. The majority are non-irrigated and include a good number of semi-natural mountain pastures and meadows. Their growth conditions are linked to water availability, thus showing a wide range of actual $K_{c\ mid}$ and $K_{c\ avg}$ values. Despite management is not referred to water but rarely, this group of papers (section "Seminatural and planted grasslands") makes it somewhat evident that ecosystem services, such like biodiversity, C sequestration, and runoff and erosion control call for more importance to be given to water use in grasslands management.

The second group (Section "Semi-natural grassland ecosystems") refers to grasslands in various typical biome, covering a wide range of environments and ecosystems, from hot and dry plains to freezing and humid mountainous areas. These types of grasses helped to identify the need for consideration of water in management of such varied types of semi-natural grasslands and to associate water and grazing management to avoid grassland deterioration and to provide for biodiversity and C sequestration.

A variety of grasses for most of environments and grassland uses are described in Section "Grasses for hay, grazing and landscape". Since they are used as planted grasses, related information is important for new plantations, using both single and combined grasses. Moreover, that

Table 8 Field derived actual single and dual crop coefficients ($K_{c\ act}$ and $K_{cb\ act}$) for grasses used for hay or grazing with multiple cut cycles

Grass crop	Reference	Location (climate)	Method to estimate ET_o and $ET_{c\ act}$	Nr. of cut cycles, other uses and season duration + *Height (h,* m*) and f_c*	Conditions relative to the reported K_c/K_{cb} + *irrigation method*	$K_{c\ act}$ or $K_{cb\ act}$ for single or multiple cuts, grazing, and seed production			
						$K_{c\ act\ avg}$	$K_{c\ act\ ini}$	$K_{c\ act\ mid}$	$K_{c\ act\ end}$
Alfalfa, *Medicago sativa*	Cavero et al. (2017)	Zaragoza, Spain (mild wint, hot sum)	FAO56-PM ET_o Testing K_c-yield SWC-grav.	6 cycles Mar–Sep $h_{ini}=0.07$, $h_{cut}=0.7$	*Sprinkler*		0.40	1.22	1.17
	Hunsaker et al. (2002)	Phoenix, Arizona, USA (arid, hot)	FAO56-PM ET_o 3 WL, neutron SWC	8 cycles Feb–Dec $h_{ini}=0.03$, $h_{cut}=0.55$ $f_c=0.80$	**K_{cb}** *Flooding*		***0.30***	***1.22***	***1.05***
	Liu et al. (2022b)	Suzhou, Gansu Province, China (very cold winter)	FAO56-PM ET_o SWC-TDR, model SIMDualKc	3 cycles Apr–Sep $h_{ini}=0.10$, $h_{cut}=0.75$	**K_{cb}** *Flooding*		***0.30***	***1.15***	***1.10***
	Allen et al. (2005a)	Imperial Valley, CA, USA (arid, hot)	FAO56-PM ET_o FAO56-dual K_c, SWB	8 cycles Feb–Oct	**K_{cb}** *Border*		***0.30***	***1.15***	***1.10***
				Seed	**K_{cb}**		***0.30***	***0.80***	***0.70***
	Hu et al. (2020)	Wuwei, Gansu, NW China (very cold winter)	FAO56-PM ET_o DL, model SIMDualKc	3 or 4 cycles May–Sep $f_c=0.97$	**K_{cb}** *Border*		***0.30***	***1.15***	***1.10***
Bermuda grass, *Cynodon dactylon*	Sanches et al. (2019)	Piracicaba, São Paulo, Brazil (subtropical)	FAO56-PM ET_o WL	11 cycles h_{low}=0.10	Avg K_c Fall	0.86	0.71	0.89	0.95
					Winter	1.00	0.85	1.08	0.95
					Spring	0.93	0.79	0.96	0.94
					Summer *Sprinkler*	1.08	0.94	1.16	1.14
Berseem clover, *Trifolium alexandrinum*	Tyagi et al. (2003)	Karnal, India (tropical subhumid)	FAO56-PM ET_o WL	5 cycles, Oct–Apr *LAI=0.35 to 3.6*	Average cuts *Flooding*		0.76	1.10	1.23
	Kaushika et al. (2019)	Roorkee and Karnal, India (tropical subhumid)	Hargreaves ET_o WL	4 cycles—Roorkee 5 cycles—Karnal	Avg. cuts Roorkee Karnal *Border*		0.30 0.30	1.20 1.15	1.15 1.10
Blue Panic, *Panicum antidotale*	Ismail and El-Nakhlawy (2018)	Hada Al-Sham, Jeddah, S Arabia (arid, hot)	FAO56-PM ET_o DL, SWB-grav.	11 cycles Jan–Dec $h_{max}=1.05\text{-}1.40$	1st cut 8th cut 11th cut *Flooding*		0.50 0.75 0.75	1.00 1.40 1.30	0.70 1.20 0.75

Table 8 (continued)

Grass crop	Reference	Location (climate)	Method to estimate ET_o and $ET_{c\ act}$	Nr. of cut cycles, other uses and season duration + *Height (h,* m*) and f_c*	Conditions relative to the reported K_c/K_{cb} + *irrigation method*	$K_{c\ act}$ or $K_{cb\ act}$ for single or multiple cuts, grazing, and seed production			
						$K_{c\ act\ avg}$	$K_{c\ act\ ini}$	$K_{c\ act\ mid}$	$K_{c\ act\ end}$
Guinea grass cv. 'Mombaça', *Megathyrsus maximus*	Sanches et al. (2019)	Piracicaba, São Paulo, Brazil (Subtropical humid)	FAO56-PM ET_o WL	10 cycles $h_{low}=0.30$	Avg cuts in Fall	1.09	0.98	1.18	1.16
					Winter	1.09	0.90	1.20	1.16
					Spring	0.95	0.80	1.08	1.09
					Summer	1.12	0.82	1.34	1.14
					Sprinkler				
	Mota et al. (2020)	Janaúba, Minas Gerais, Brazil (subtropical)	FAO56-PM ET_o DL	4 cycles Summer + 3 cycles Fall	Avg Summer		0.79	1.20	1.20
					Avg Fall		0.74	1.21	1.21
				3 cycles Win-Spg	Avg Win-Spg		0.62	1.06	1.06
				$h_{cut}=0.45\text{-}0.90$	*Sprinkler*				
	Bueno et al. (2009)	Uberlândia, Minas Gerais, Brazil (tropical)	Grass lysimeter	3 cycles grazing cuts $h_{ini}=0.20$	Average cuts *Sprinkler*		0.75	0.83	1.04
Palisade grass (cv. 'Marandú'), *Brachiaria brizantha*	Souza et al. (2021)	Piracicaba, São Paulo, Brazil (subtropical)	FAO56-PM ET_o DL	11 cycles Feb–Dec $h_{ini}=0.15, f_c=0.95$	Spring–Summer		0.50	0.90	0.90
					Fall-Winter		0.67	0.85	0.80
					Sprinkler				
	Antoniel et al. (2016)	Maringá, Paraná, Brazil (Subtropical humid)	FAO56-PM ET_o Field tested K_c values	4 cycles	1st cut	0.90			
					3^{rd} cut	1.33			
					3rd cut	1.24			
					4^{th} cut	1.02			
					Sprinkler				
Sudan grass, *Sorghum sudanense*	Allen et al. (2005a)	Imperial Valley, South CA, USA (arid, hot)	FAO56-PM ET_o FAO56-K_{cb}, SWB	Cuts for hay	***K_{cb}*** *Border*		***0.30***	***1.10***	***1.05***
	Al-Solaimani et al. (2017)	Hada Al-Sham, Jeddah, Saudi Arabia (arid, hot)	FAO56-PM ET_o SWB-grav.	3 cycles May–Feb $h_{cut}=1.20$	Average cuts *Border*		0.50	0.85	

Symbols, abbreviations and acronyms are given in Appendix B

Bold italics are to highligh that these values are K_{cb} which differ from the other values which are K_c

Table 9 Field derived actual single and dual crop coefficients ($K_{c\,act}$ and $K_{cb\,act}$) for grasses cropped for grazing and seed production

Grass crop	Reference	Location (climate)	Method to estimate ET_o and $ET_{c\,act}$	Nr. cut cycles, other uses and season duration *height (h, m), f_c*	Conditions relative to observed K_c/K_{cb} + *irrigation method*	$K_{c\,act}$ or $K_{cb\,act}$ for single or multiple cuts, grazing, and seed production			
						$K_{c\,act\,avg}$	$K_{c\,act\,ini}$	$K_{c\,act\,mid}$	$K_{c\,act\,end}$
Bahiagrass, *Paspalum notatum*	Sumner and Jacobs (2005)	Floral City, West Florida, USA (subtropical humid)	ASCE-PM ET_o EC	Rotational grazing	Full year *Rainfed*		0.59	0.95	0.45
	Jia et al. (2009)	Citra, Gainsville, Florida, USA (subtropical humid)	ASCE-PM ET_r EC, SWB-Hydra, PT eq.	Grazing *h_{low}=0.12*	Full year *Linear move*		0.40	0.86	0.52
Bermuda grass, *Cynodon dactylon*	Allen et al. (2005a)	Imperial Valley, CA, USA (arid, hot)	FAO56-PM ET_o FAO56-dual K_c, SWB	Grazing Seed	$\boldsymbol{K_{cb}}$ $\boldsymbol{K_{cb}}$ *Border*		***0.50*** ***0.15***	***0.95*** ***0.85***	***0.80*** ***0.60***
	Paredes et al. (2018) (Tifton 85)	Santa Maria, Rio Grande do Sul, Southern Brazil (subtropical humid)	FAO56-PM ET_o SWB-TDR, model SIMDualKc	Grazing cuts when *h_{ini}=0.15, $f_{c\,ini}$=0.8* CGDD=124°C *h_{cut}=0.19 $f_{c\,cut}$=0.9* CGDD=248°C *h_{cut}=0.23 $f_{c\,cut}$=0.9* CGDD=372°C *h_{cut}=0.30 $f_{c\,cut}$=0.9*	CGDD=124 °C CGDD=248 °C CGDD=372 °C *Sprinkler*	$\boldsymbol{K_{c\,avg}}$ 0.96 0.99 1.00	$\boldsymbol{K_{cb\,ini}}$ ***0.83*** ***0.85*** ***0.87***	$\boldsymbol{K_{cb\,mid}}$ ***0.86*** ***0.91*** ***0.96***	$\boldsymbol{K_{cb\,end}}$ ***0.87*** ***0.93*** ***0.97***
Birdsfoot trefoil, *Lotus corniculatus*	Garcia-Diaz and Steiner (1999)	Corvallis, Oregon, USA (cold winter)	FAO24 Pan ET_o SWB-neutron	Seed	Summer season (83 to 100 days) *Sprinkler*	1.05			
Chinese ryegrass, *Leymus chinensis*	Wu et al. (2016)	Agula, Horqin Sandy Land, Inner Mongolia, China (freezing winter)	FAO56-PM ET_o SWB-neutron, model SIMDualKc	Grazing May-Oct *h_{max}=0.50* *$f_{c\,max}$=0.92*	$\boldsymbol{K_{cb}}$ K_c *GW fed*		***0.30*** 0.39	***0.70*** 0.77	***0.40*** 0.58
Creeping wildrye, *Leymus triticoides*	Benes et al. (2012)	Five Points, Fresno, CA, USA (mild wint, hot sum)	CIMIS-PM-ET_o DL, SR	Grazing *h =0.15-0.30*	Annual Summer *Flooding*	0.92 1.11			
Hairy vetch, *Vicia villosa*	Bodner et al. (2007)	Hollabrunn, eastern Austria (temperate)	FAO56-PM ET_o DualKc method	Grazing or cover crop *f_c=0.93*	$\boldsymbol{K_{cb}}$ *Rainfed*			***0.90***	
Italian ryegrass, *Lolium multiflorum*	Attarod et al. (2009)	Fuchu, Tokio, Japan (temperate)	FAO56-PM ET_o BREB	n/r	January to May *n.r.*	0.87			
	Mueller et al. (2005)	Paulinenaue, NW Berlin, Germany (temperate)	FAO56-PM ET_o GW Lys.	2 or 3 cut/y Apr-Sep	WTD=0.5–0.7 m WTD=0.7–1.0 m *GW fed*	0.99 0.87			
Paspalum, seashore paspalum, *Paspalum vaginatum*	Benes et al. (2012)	Five Points, Fresno, CA, USA (mild win, hot sum)	CIMIS-PM-ET_o DL	Grazing *h = 0.15-0.30*	Annual Summer *Flooding*	0.85 1.00			
Red clover, *Trifolium pratense*	Mueller et al. (2005)	Paulinenaue, Berlin, Germany (temperate)	FAO56-PM ET_o GW Lys.	2 or 3 cut/y Apr-Sep	WTD=0.4–0.7 m WTD=0.7–1.1 m *GW fed*	1.13 0.86			

Table 9 (continued)

Grass crop	Reference	Location (climate)	Method to estimate ET_o and $ET_{c\ act}$	Nr. cut cycles, other uses and season duration *height (h, m), f_c*	Conditions relative to observed K_c/K_{cb} + *irrigation method*	$K_{c\ act}$ or $K_{cb\ act}$ for single or multiple cuts, grazing, and seed production			
						$K_{c\ act\ avg}$	$K_{c\ act\ ini}$	$K_{c\ act\ mid}$	$K_{c\ act\ end}$
Rye grass, *Lollium* spp.	Allen et al. (2005a)	Imperial Valley, CA, USA (arid, hot)	FAO56-PM ET_o FAO56-K_{cb}, SWB	Grazing	***K_{cb}*** *Border*		***0.85***	***1.00***	***0.90***
	Graham et al. (2016)	Canterbury Plains, N Zealand (Temperate)	FAO56-PM ET_o PT eq.	Seed and grazing *h_{low}=0.15*	Seed Grazing *Border*		n/r n/r	0.93 0.93	0.35 n/r
Sedge grass, *Carex* spp.	Allen et al. (2005b)	Montpelier, Idaho, USA (subhumid cold)	ASCE-PM ET_r Lys. + METRIC	Grazing	July–October *Rainfed*	0.69	n/r	0.80	0.50
Sunn hemp, *Crotalaria juncea*	Takagi et al. (2009)	Tottori, Japan (temperate)	FAO56-PM ET_o BREB	Grazing *h_{max}=1.05*	*Sprinkler*		0.89	1.13	1.10
Tall fescue, *Festuca arundinacea*	Pinnix and Miller (2019)	Lake Wheeler, Raleigh, NC, USA (temperate)	ASCE-PM ET_o Small WL	Grazing *h_{low}=0.10*	Summer *Sprinkler*	0.80			
	Alam et al. (2019)	Armidale, Australia (temperate)	FAO56-PM ET_o Evap. chamber	Grazing *LAI_{max}=4.*	*Surface*		0.30	0.80	
Tall wheatgrass, *Thinopyrum ponticum*	Benes et al. (2012)	Five Points, Fresno, CA, USA (mild wint, hot sum)	CIMIS-PM-ET_o DL, SR	Grazing *h = 0.15 to 0.30* *f_c=0.98*	Annual Summer *Flooding*	0.98 1.08			
Timothy, *Phleum pratense*	Mueller et al. (2005)	Paulinenaue, NW Berlin, Germany (temperate)	FAO56-PM ET_o GW Lys.	2 or 3 cut/year Apr–Sep	WTD=0.5-0.8 mWTD=0.8–1.1 m *GW fed*	0.86 0.78			

Symbols, abbreviations and acronyms are given in Appendix B

Bold italics are to highligh that these values are K_{cb} which differ from the other values which are K_c

Table 10 Field derived actual single crop coefficients (K_c) for landscape grasses

Grass crop	Reference	Location (climate)	Method to estimate ET_o and $ET_{c\ act}$	Uses, season duration, height (h) and f_c	Conditions relative to the reported K_c + *irrigation method*	$K_{c\ act}$ or $K_{cb\ act}$ for mowing for landscape, sport and gulf courses			
						$K_{c\ act\ avg}$	$K_{c\ act\ ini}$	$K_{c\ act\ mid}$	$K_{c\ act\ end}$
Bahiagrass, *Paspalum notatum*	Migliaccio and Shoemaker (2014)	Snapper Creek, S. Florida, USA (subtropical humid)	FAO56-PM ET_o EC, PT eq.	Urban Full year	*Rainfed*		0.67	0.83	0.62
	Wherley et al. (2015)	Citra, Florida, USA (subtropical humid)	ASCE-PM ET_o WL	Lawn, mowed to h = 0.088	*Rainfed*	0.75			
Bentgrass, *Agrostis stolonifera*	Bandenay et al. (2021)	Castellón, Valencia Spain (mild wint, hot sum)	FAO56-PM ET_o DL, SWB-capacit.	Golf green, Mar–Nov f_c = 1.0	Current With hydrogel+OM *Diffusers*	1.06 1.18			
Bermuda grass, *Cynodon dactylon*	Bañuelos et al. (2011)	Karsen, Arizona, USA (arid, hot)	FAO56-PM ET_o SWB-TDR	Golf h = 0.016, f_c = 0.97	Summer *Sprinkler*	0.80			
Bermuda grass, *Cynodon dactylon × C. transvaalensis*	Wherley et al. (2015)	Citra, Florida, USA (subtropical)	ASCE-PM ET_o WL	Lawn h_{low}=0.05	*Sprinkler*	0.67			
	Pinnix and Miller (2019)	Lake Wheeler, Raleigh, NC, USA (temperate)	ASCE-PM ET_o Small WL	Landscape h_{low}=0.05	Summer *Sprinkler*	0.56			
Blue fescue, *Festuca glauca*	Yuan et al. (2011)	Changping, Beijing, China (cold wint, hot sum)	FAO56-PM ET_o Mini WL	Landscape	May-Oct *Sprinkler*			0.80	0.14
Feather reed grass, *Calamagrostis brachytricha*	Yuan et al. (2011)	Changping, Beijing (cold wint, hot sum)	FAO56-PM ET_o Mini WL	Landscape	May-Oct *Sprinkler*			1.05	0.48
Paspalum, seashore paspalum, *Paspalum vaginatum*	Bañuelos et al. (2011)	Karsen, Arizona, USA (arid, hot)	FAO56-PM ET_o SWB-TDR	Landscape, gulf h = 0.016, f_c = 0.90	Summer *Sprinkler*	0.80			
St. Augustinegrass, *Stenotaphrum secundatum*	Fontanier et al. (2017)	College Station, TX, USA (temperate)	FAO56-PM ET_o SWB-TDR	landscape f_c = 1.0	Season *Sprinkler*	0.80			
	Wherley et al. (2015)	Citra, Florida, USA (subtropical humid)	ASCE-PM ET_o WL	Lawn, mowed to h_{low}=0.088	*Sprinkler*	0.63			
Zoysiagrass, *Zoysia japonica*	Wherley et al. (2015)	Citra, Florida, USA (subtropical humid)	ASCE-PM ET_o WL	Lawn, mowed to h_{low}=0.051	*Sprinkler*	0.69			

Symbols, abbreviations and acronyms are given in Appendix B

Table 11 Standard K_c values for semi-natural and planted grasslands and for grasses for agricultural and landscape uses

Typical grasslands and grasses for animal feeding, landscape and sport	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
Semi-natural high mountain meadows and grasslands for grazing and hay, freezing winter, short mid-season, killing frost	0.40	1.10	0.95
Semi-natural high mountain meadows and grasslands for grazing and hay, freezing winter, no killing frost	0.40	1.00	0.35
Non-irrigated grasslands and meadows in low elevation plateau and prairies for grazing or seed, cold winter but large mid-season	0.55	0.95	0.50
Non-irrigated grasslands and meadows in low elevation plateau and prairies for hay, cold winter but large mid-season (K_c for typical cut cycles)	0.45	1.15	1.15
Irrigated grasslands, meadows, and pastures for grazing or seed, cold/mild winter and large mid-season	0.55	1.05	0.55
Irrigated grasslands, meadows, and pastures for hay, cold/mild winter and large mid-season (K_c for typical cut cycles)	0.55	1.05	1.05
Semi-natural savanna grasslands	0.35	0.90	0.35
Semi-natural steppe grasslands	0.30	0.75	0.30
Semi-natural meadows and pastures in high mountain	0.40	1.00	0.45
Semi-natural cold and temperate grassland ecosystems	0.40	0.65	0.45
Semi-natural mixed grasslands and forests/woodlands	0.35	0.70	0.40
Semi-natural shrublands	0.25	0.70	0.40
Grasses			
Alfalfa for hay; typical cuts cycles	0.50	1.20	1.15
Alfalfa for seed	0.40	1.10	0.65
Grasses for grazing, high height of grazing cuts	0.90	1.05	0.90
Grasses for grazing, low height of grazing cuts	0.85	0.95	0.85
Grasses for grazing with large cut cycles	0.90	0.95	0.95
Grasses for seed production	0.30	0.90	0.65
Grasses for grazing with short cut cycles	0.85	0.95	1.00
Grasses for hay; typical cuts cycles	0.55	1.15	1.05
Landscape grasses, golf courses (cut $h<0.01$ m)	0.80	0.80	0.80
Landscape grasses, lawns (cut $h<0.10$ m)	0.50	0.70	0.50
Landscape grasses, urban	0.65	0.90	0.50

information is useful for irrigation management and scheduling applied to irrigated grasslands. Related applied research should be developed aiming at improved water productivity and water saving since such information is rare.

K_c values tabulated for that wide number of grasslands and grasses may be useful for feeding all kind of herbivorous, for landscape and for sport activities, always considering the need for saving water, i.e., to avoid excess water application and, on the contrary, to avoid detrimental water deficits that reduce both the productivity and the ecosystem services. It is opportune to refer the need for continuing research that may not only increase the transferable case studies data but also may support improving the summarized standard K_c values (Section "Standard crop coefficients") for use in Hydrology and water resources. This review led to conclude that research on grass productivity should also consider issues for ecosystem services.

Research aimed at ecosystem services requires however a better consideration of the role that water plays to improve biodiversity, C sequestration, water infiltration, thus controlling runoff and erosion, improving water availability through storage in the soil and in groundwater, thus contributing to mitigate effects of climate extremes and climate change, particularly in case of semi-natural grasslands. More research is required along these lines as well as relative to policy making that could contribute to define related priorities and the protection of semi-natural grasslands, as well supporting the mitigation of impacts of global change.

Appendix A

See Tables 12, 13 and 14.

Table 12 Characteristics of selected semi-natural high elevation grasslands.

Identification	Reference	Climate	Methods for detemining ET_o and $ET_{c\ act}$	Season period	Water supply
Alpine pasture, Torgnon, Aosta Valley, Italy	Corbari et al. (2017)	Freezing winter, mild summer	FAO56-PM ET_o EC, RS-VI, PM eq.	May–Sep	Rainfed
Mountain grasslands of Aosta Alps, Italy	Gisolo et al. (2022)	High mountain freezing winter	FAO-PM-ET_o EC, METRIC, SWB-CLIME-MG model	Apr–Sep or Oct	Rainfed
Alpine grasslands in Canton of Valais, Switzerland	Smith et al. (2012)	High mountain freezing winter	FAO-PM-ET_o K_c from LAI	Apr–Sep Apr–Oct	Mostly rainfed
Andean Zhurucay páramo, Cajas Massif, Southern Equador	Carrillo-Rojas et al. (2019)	Alpine Equatorial	FAO56-PM ET_o EC	Annual	Rainfed
High elevation Andean páramos, Machangara, southern Ecuador	Buytaert et al. (2006)	Cold and rainy	FAO56-PM ETo Basin water balance	Annual	Rainfed
Humid alpine meadow, Haibei, Qinghai-Tibetan Plateau, China	Dai et al. (2021)	Freezing winter	FAO56-PM ET_o WL, FAO56	Growing season	Rainfed
Subalpine meadows, Heihe River, Qilian Mountains, China	Gao et al. (2019)	Semi-arid, very cold winter	FAO56-PM ET_o EC	May-Oct	Rainfed
High mountain meadow, Yeniugou, Qilian Mountains, China	Yang et al. (2013)	Very cold winter with frozen soil	FAO56-PM ET_o Mini-Lys.	Jun-Sep	Rainfed
Alpine meadow, Heihe basin, Qilian Mountains, China	Yang et al. (2017)	Very cold winter with frozen soil	FAO56-PM ET_o WL, SWB-Trime	Annual	Rainfed
Alpine meadow of the Tibetan Plateau, China	Chang et al. (2017)	Very cold winter	FAO56-PM ET_o EC	Apr/May Sep/Oct	Rainfed
Humid meadow, Fenghuoshan, Qinghai-Tibetan Plateau, China	Li and Wang (2015)	Very cold winter	FAO56-PM ET_o EC	May–Sep	Rainfed
Alpine meadow, Qinghai Tibetan Plateau, China	Li et al. (2013)	Very cold winter	FAO56-PM ET_o EC	May–Sep	Rainfed
Global ecosystem ET/ET_o FluxNet	Liu et al. (2017)	Diverse climates	FAO-PM-ET_o, Global eddy flux	n/r	n/r

Table 13 Characteristics of selected non-irrigated grasslands in low elevation mountains and lowlands.

Identification	Reference	Climate	Methods for detemining ET_o and $ET_{c\ act}$	Management f_c and h(m)	Season period	Water supply
Groundwater fed pasture in Horqin Sandy Land of Inner Mongolia, China	Wu et al. (2016)	Very cold winter	FAO56-PM ET_o SWB-SIMDualKc	Grazing	May–Oct	GW fed
Grasslands of Xilin, Inner Mongolia, China	Zhao et al. (2010)	Very cold winter	FAO56-PM ET_o SWB-Theta-probes	Grazing	May–Sep	Rainfed
Grassland and shrubland in Zhanggutai , Liaoning, China	Zheng et al. (2012)	Monsoon, cold winter	FAO56-PM ET_o SWB-CROPWAT, RS	n/r	May–Sep	Rainfed
Chippewa prairie grasslands, West-Central Minnesota, USA	Baeumler et al. (2019)	Cold winter	ASCE-PM ET_r METRIC model	Grazing	Growing season	Rainfed
Perennial pastures, Central Valley of California + Carson Valley Nevada, USA	Howes et al. (2015)	Temperate	FAO56-PM ET_o Review and re-computing	Grazing	Annual	GW fed
Gudmundsen Sand Hills meadow, Nebraska, USA	Healey et al. (2011)	Cold winter	ASCE-PM ET_r BREBS, METRIC	Grazing and cutting	Apr–Oct	GW fed
Tallgrass prairie at Stillwater, Oklahoma, USA	Krueger et al. (2021)	Temperate	FAO56-PM ET_o EC, SWB and grass ET model	Grazing f_c=0.88, h_{max}=0.75	Annual	Rainfed
Pastureland at Hillsborough County, Central Florida, USA	Nachabe et al. (2005)	Subtropical humid	Class A Pan ET_o SWB-capacit.	Grazing	Annual	GW fed
Pasture in Floral City, central Florida, USA	Sumner and Jacobs (2005)	Humid sub-tropical	ASCE-PM ET_o EC	Rotational grazing	Annual	Rainfed
Grassland in North Dakota, USA	Niaghi and Jia (2017)	Continental sub-humid	ASCE-PM ET_o EC, SWB–Hydra	Grazing and hay	Apr–Oct	Rainfed
Meadow and grasslands in northern New York State, USA	Hwang et al. (2020)	Cold winter	FAO-PM-ET_o, BREB, SEBS	Grazing Apr–Oct	Apr–Oct	Rainfed
Intensively grazed pasture, Waikato, New Zealand	Pronger et al. (2016)	Temperate	FAO56-PM ET_o EC	Grazing h = 0.50–0.70	Annual	Rainfed
Wetlands in Upper Pangani River Basin, Tanzania,	Kiptala et al. (2013)	Tropical semiarid, hot	FAO24-Pan-ET_o SEBAL and RS-Modis	Grazing	Annual	Rainfed
Mountain semi-natural pastures in Montalegre, northern Portugal	Pôças et al. (2013)	Cold winter, humid	FAO56-PM ET_o EB, METRIC	Grazing	Mar–Nov	Rainfed
Pasture at Ribeirinha, Terceira Island, Azores	Fontes et al. (2004)	Temperate humid	FAO-PM-ET_o Basin WB-OPUS	Rotational grazing	Annual	Rainfed
Wet Grasslands at Havelländisches Luch (HL)and Spreewald Wetland (SW), eastern Germany	Dietrich et al. (2021)	Temperate, cold winter	FAO56-PM ET_o EC (PO), WL (CO)	Grazing	May–Sep	Rainfed, GW fed
Grassland in Rollesbroich, LowRhine Valley, Germany.	Groh et al. (2015)	Cold winter, sub-humid	FAO56-PM ET_o WL	Cuts in May, Jul, Aug, Nov	Apr–Nov	Rainfed
Mountain pasture sward in the Western Carpathians, Poland	Kuźniar et al. (2011)	Cold humid winter	FAO56-PM ET_o Reviewed data	n/r	May–Oct	Rainfed
Meadows in Poland	Kasperska-Wołowicz and Łabędzki (2006)	Cold humid winter	FAO56-PM ET_o DL, SWB	Grazing and cutting	Apr–Sep	n/r
Pastures and meadow in North-East Poland	Szejba (2011)	Cold humid winter	FAO56-PM ET_o Review grass K_c	Grazing. hay, 3-cuts	May–Sep	Rainfed
Grass by the Fenéka pond edge, Kis-Balaton Lake, Hungary	Anda et al. (2015)	Cold humid winter	FAO56-PM ET_o Modified DL	Grazing	May–Oct	Rainfed

Table 14 Field observed K_c and K_{cb} for irrigated grasslands, meadows, and pastures

Identification	Reference	Climate	Methods for determining ET_o and $ET_{c\ act}$	Management f_c and h (m)	Season period	Irrigation method
Pasture in Gareh Bygone Plain, South of Zagros, Shiraz, Iran	Pakparvar et al. (2014)	Continental, semi-arid	FAO-PM-ET_o, RS-SEBS	Grazing $h = 0.32$, $f_c = 0.67$	Annual	Border DI
Dairy pastures in the Goulburn-Murray District, Victoria, Australia	Abuzar et al. (2017)	Temperate	FAO56-PM ET_o RS-NDVI, SWB-FDR	Grazing	Annual	Sprinkler, border
Irrigated pasture in Murray-Darling basin, Australia	Bethune and Wang (2004)	Temperate	Grass WL-ET_o SWB, SWAT	Grazing $f_c = 1.00$	Annual	Border irrigation
Irrigated grasses at at Kyabram, northern Victoria, Australia	Greenwood et al. (2009)	Temperate	FAO56-PM ET_o SWB-neutron, dualK_c model	$f_c = 0.97$	n/r	Border Irrigation
Irrigated pasture in northern Victoria, Australia	Qassim et al. (2008)	Temperate	FAO56-PM ET_o BREB, PT+PMeq	Grazing	Annual	Centre pivot
Research pastures at New England University, NewSouth Wales, Australia	Alam et al. (2018)	Temperate	FAO56-PM ET_o ET dome with RH + T sensors	Grazing, mowing $h_{low}=0.05$	Annual	Irrigated
Grazing pastures, Christchurch, New Zealand	KC et al. (2018)	Temperate	FAO56-PM ET_o SWB-mini DL, Aquaflex sens.	Grazing $h = 0.05\text{-}0.30$	Annual	Center-pivot
Meadows in mountain areas of Montalegre, Portugal	Pôças et al. (2013)	Cold winter	FAO56-PM ET_o METRIC	Hay and grazing	Mar-Oct	Contour ditches
Pastures in Terra Chá, Lugo, Galize, Spain	Cancela et al. (2006)	Temperate	FAO56-PM ET_o SWB ISAREG	Grazing, mowing	Apr-Oct	Sprinkler FI
Irrigated grasses at Piracicaba, São Paulo, Brazil	Sanches et al. (2019)	Subtropical humid with hot summers	FAO56-PM ET_o Plot small WL	6 or 7 cycles 5 cycles	Annual $h_{low=}0.30$ $h_{cut}=0.60$	Sprinkler
"Marandu" palisade grass, single and combined, in Piracicaba, Brazil	Souza et al. (2021)	Subtropical humid	FAO56-PM-ET_o WL	Grazing	Annual	Sprinkler
Irrigated pasture at Twitchell Island, Sacramento river, and	Snyder et al. (2008)	Dry and hot summer	ASCE-PM ET_o Surf. renewal	Grazing $h_{cut}=0.10\text{-}0.20$	n/r	Basin irrigation
Campbell Tract, Davis, USA				$h_{cut}=0.08\text{-}0.12$	n/r	Sprinkler
Bahiagrass in Citra, Central Florida, USA	Jia et al. (2009)	Subtropical humid	ASCE-PM ET_o EC, SWB-Hydra	Grazing	Annual	Linear-move
Permanent pastures at Imperial Valley, CA, USA	Allen et al. (2005a)	Dry, hot summer	FAO56-PM ET_o FAO56-K_{cb}, SWB	Grazing, f_c=1.0	Annual	Border

Appendix B. List of symbols, abbreviations, and acronyms

ET_c	Crop evapotranspiration under standard conditions [mm d^{-1} or mm h^{-1}]
$ET_{c\ act}$	Actual crop evapotranspiration, i.e., under non-standard conditions [mm d^{-1} or mm h^{-1}]
ET_o	(grass) reference crop evapotranspiration [mm d^{-1} or mm h^{-1}]
ET_r	Alfalfa reference crop evapotranspiration [mm d^{-1} or mm h^{-1}]
f_c	Fraction of soil surface covered by vegetation (as observed from overhead) [-]
h_{cut}	Crop height before cutting [m]
h_{low}	Crop height after mowing or cutting [m]
h_{max}	Crop height before mowing or grazing [m]
K_c	(standard) crop coefficient [-]
$K_{c\ act}$	Actual crop coefficient (under non-standard conditions) [-]
$K_{c\ avg}$	(standard) average crop coefficient [-]
$K_{c\ ini}$	Crop coefficient during the initial growth stage [-]
$K_{c\ mid}$	Crop coefficient during the mid-season growth stage [-]
$K_{c\ end}$	Crop coefficient at end of the late season growth stage [-]
$K_{c\ cut}$	Crop coefficient before cutting [-]
$K_{c\ high}$	Crop coefficient prior to grazing starts [-]
$K_{c\ low}$	Crop coefficient at the end of grazing [-]
K_{cb}	Standard basal crop coefficient [-]
$K_{cb\ act}$	Actual basal crop coefficient (under non-standard conditions and/or observed) [-]
$K_{cb\ ini}$	Basal crop coefficient during the initial growth stage [-]
$K_{cb\ mid}$	Basal crop coefficient during the mid-season growth stage [-]
$K_{cb\ end}$	Basal crop coefficient at end of the late season growth stage [-]
K_s	Water stress coefficient [-]
PET	Potential evapotranspiration [mm d^{-1} or mm h^{-1}]
T_c	Crop transpiration [mm d^{-1} or mm h^{-1}]

Abbreviations and acronyms

ASCE-PM-ET_r	Alfalfa reference ET_r calculated using an extension of the FAO56 Penman-Monteith equation
Avg.	Average
BREB	Bowen ratio energy balance
Capacit.	Capacitance sensors
CGDD	Cumulative growing degree day [^{o}C]
DL	Drainage lysimeters
EC	Eddy covariance
ECV-SM	European Space Agency and Climate Change Initiative merged soil moisture product
EVI	Enhanced Vegetation Index
FAO	Food and Agriculture Organization
FAO56	Food and Agriculture Organization Irrigation and Drainage Paper 56 (1998)
FAO56-PM-ET_o	Grass reference ET_o computed with the FAO56 standardized Penman-Monteith equation
FLUXNET	Global network of micrometeorological flux measurement sites
GHG	Greenhouse gas
Grav.	Gravimetric method
GW	Groundwater
GW Lys.	Water table lysimeter
HWB	Field or catchment hydrologic water balance
J&H	Jensen and Haise equation
LAI	leaf area index
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
PM-eq.	Penman-Monteith combination equation
PT	Priestley-Taylor equation
Reflect.	Reflectometer
RS	Remote sensing
SAFER	Simple Algorithm for Evapotranspiration Retrieving
SAVI	Soil adjusted vegetation Index
SEB	Surface energy balance
SEBAL	Surface Energy Balance Algorithm for Land model
SEBS	Surface Energy Balance System model
SF	Sap flow
SOC	Soil organic carbon
Spg	Spring
Spr	Sprinkler
SR	Surface renewal
Sum.	Summer
SW	Double source method of Shuttleworth and Wallace
SWB	Soil water balance
SWC	Soil water content
Tens.	Tensiometers
Trime	Trime-EZ soil moisture sensors

UN	United Nations
VI	Vegetation index
Win	Winter
WL	Weighing lysimeter

Appendix C. Scientific and common names of the plants mentioned in the previous Tables

Scientific name	Common name	Scientific name	Common name
Acacia spp.	Wattle, mimosa, thorntee	*Festuca rubra*	Creeping red fescue
Acacia etbaica	Clownhair wattle	*Festuca* spp.	Fescue grass
Acacia senegal	Gum Acacia, Gum Arabic Tree, or Gum Senegal Tree	*Foeniculum vulgare*	Common fennel
Acacia victoria	Gundabluie, or bardi bush	*Geoffroea* spp.	Chanar, Chilean Palo Verde
Achnatherum sibiricum	Siberian Needlegrass	*Geranium* spp.	Cranesbills
Aegilops crassa	Persian goatgrass	*Haloxylon ammodendron*	Saxaul
Aristida affinis = A. purpurascens	Arrowfeather threeawn	*Helianthemum lippii*	Raqrouq
Aristida laevis	Aristida grass	*Holcus lanatus*	Yorkshire fog, fog grass
Agrostis spp.	Bentgrass	*Iriantus angustifolium*	
Agrostis stolonifera	Bentgrass, creeping bent	*Kobresia* sp	Perennial sedge.
Alisma spp.	Water-plantain	*Kobresia capillifolia*	*= Carex capillifolia*
Andropogon gerardii	Big blue stem	*Kobresia humilis*	*= Carex alatauensis*
Andropogon lateralis	Beard grass, bluestem grass, broomsedge	*Kobresia pygmaea*	*= Carex parvula*
Arnica montana	Wolf's bane, leopard's bane, mountain tobacco, m. arnica	*Kobresia tibetica*	*= Carex tibetikobresia*
Artemisia frigida	Silky wormwood	*Leymus chinensis*	Chinese ryegrass
Artemisia ordosica		*Leymus triticoides*	Creeping wildry
Artemisia sieberi		*Lolium multiflorum*	Italian ryegrass
Artemisia tridentata	Sagebrush	*Lolium perenne*	Perennial ryegrass, English ryegrass
Hordeum leporinum	Barley-grass	*Lollium* spp.	Ryegrass
Atriplex lentiformis	Quail bush, big saltbush	*Lotus corniculatus*	Birdsfoot trefoil
Avena barbata	Slender wild oat, bearded oat	*Medicago polymorpha*	California burclover, toothed bur clover, or toothed medick
Avena strigosa, Avena fatua	Black oats	*Medicago sativa*	Alfalfa
Axonopus affinis	Common carpetgrass	*Medicago* spp.	Medick, burclover
Bassia dasyphylla	Shaggy-Leaved Bassia	*Megathyrsus maximus*	Guinea grass cv. ‘Mombaça’
Bouteloua gracilis	Blue grama	*Nardus stricta*	Matgrass
Brachiaria brizantha	Palisade grass (‘Marandú’)	*Ornithopus compressus*	Yellow bird's-foot
Bromopsis inermis	Smooth brome	*Panicum antidotale*	Blue panic, giant panic-grass
Bromus spp.	Brome	*Pascopyrum smithii*	Wheatgrass
Calamagrostis brachytricha	Feather reed grass, foxtail grass, diamond grass	*Paspalum* spp.	Bahiagrass, crowngrass or dallis grass
Calamagrostis spp.	Tussock grasses	*Paspalum dilatatum*	Dallis grass
Carex atrofusca	Dark brown sedge or scorched alpine sedge	*Paspalum notatum*	Bahiagrass
Carex moorcroftii		*Paspalum piptochaetium*	
Carex sempervirens	Evergreen sedge	*Paspalum vaginatum*	Paspalum, seashore paspalum
Carex spp.	Sedge grass	*Phalaris arundinacea*	Reed canary grass
Carissa edulis	Climbing num-num, simple-spined num-num	*Phleum pratense*	Timothy grass, cat’s tail
Carya spp.	Hickory	*Pinus koraiensis*	Korean pine
Celtis sp.	Hackberry	*Pinus pinaster*	Maritime pine, cluster pine
Cerastium spp.	Mouse-ear chickweed	*Pinus pinea*	Stone pine, Roman pine, parasol pine, umbrella pine

Scientific name	Common name	Scientific name	Common name
Chrysothamnus nauseosus	Chamisa, rubber rabbitbrush, and gray rabbitbrush	*Pinus ponderosa*	Ponderosa pine
Cirsium spp.	Thistle	*Plantago lanceolata*	Buckhorn plantain
Crotalaria juncea	Sunn hemp	*Poa angustifolia*	Narrow-leaved meadow grass
Cynodon dactylon	Bermudagrass	*Poa pratensis*	Kentucky bluegrass
Cynodon dactylon × *C. transvaalensis*	Hybrid Bermudagrass	*Poa* spp.	Meadow-grass, bluegrass, tussock and speargrass
Cynosurus cristatus	Crested dogtail grass	*Polylepis* spp.	Tabaquillo
Cytisus spp.	Broom	*Populus euphratica*	Euphrates poplar
Dactylis glomerata	Cat grass, cocksfoot	*Populus* spp.	Poplar Tree
Deschampsia cespitosa	Turfed hair grass	*Prosopis* spp.	Mesquite
Dichanthelium spp.	Witch grass	*Quercus faginea*	Portuguese oak
Dodonea angustifolia	Sand olive	*Quercus ilex*	Holm
Elymus nutans		*Quercus rotundifolia*	Holm
Elymus smithii	Wildrye, wheatgrass, squirreltail	*Quercus* spp.	Oak trees
Erica spp.	Heaths	*Trifolium repens*	White clover
Fagus sylvatica	Beech	*Trifolium resupinatum*	Persian clover
Festuca arundinacea	Tall fescue grass	*Trifolium subterraneum*	Subterranean clover
Festuca glauca	Blue fescue		Short bunchgrass
Festuca nigrescens	Chewing's fescue		

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Declarations

Conflict of interest The authors declare no competing interests.

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