› Sustainable irrigation of date palms in the hyper-arid United Arab Emirates: a review

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Introduction

Dates (*Phoenix dactylifera* L.) are important for heritage, cultural, religious, and economic reasons in the Middle East, South Asia and North Africa. These regions are arid and hyper-arid and so the date palm-trees need to be irrigated. Traditionally, date palms were sustainably irrigated using groundwater resources. Since ancient times, in the United Arab Emirates (UAE) and across the Arabian Peninsula, so-called *aflaj* systems were used to supply water to irrigate the palms, *inter alia*. These *aflaj* systems drained groundwater from higher elevations under gravity through man-made tunnels eventually bringing the groundwater to the surface. From this now-surface source, water was then distributed through channels for irrigation, plus it was also used for household and religious purposes (http://whc.unesco.org/en/list/1207/). In classical Arabic, *aflaj* (the singular is *falaj*) means to 'split into parts'. Dates were traditionally grown in surface irrigated basins in which there was usually also a cover crop that could grow under the canopy of the date palms.

Groundwater remains the prime source of irrigation water in the regions, but due to increased demands for irrigation, and via modern pumping systems, it is under threat from declining quantity and rising salinity. Usage of groundwater now well exceeds the rate of natural replenishment in this hyper-arid region. While there are merits in seeking to improve the efficiencies of modern irrigation systems, regulatory solutions need to be found to protect the natural capital stocks of groundwater. Of fundamental importance is the need to determine the actual water requirements of date palms under these hyper-arid conditions. Here we review our work in the hyper-arid UAE on developing sustainable rates of irrigation that can be used for regulatory purposes. We also highlight the benefits that can accrue from using solar-power desalinated water to irrigate palm trees, as well as detailing the concerns that would ensue from the disposal of the reject brine from these desalination units.

Figure 1. A. One of the instrumented 'Lulu' date palms from the S1 treatment that was irrigated with water at 5 dS m^{-1}. The tree height was 3.6 m, and the irrigation bund surrounding the tree can be seen. B. One of the instrumented 'Lulu' date palms from the S3 treatment that was irrigated with water at 15 dS m^{-1}. The tree height was 2.6 m. The experimental site is at the International Center for Biosaline Agriculture near the city of Dubai, United Arab Emirates, and the photos were taken in 2014.

History of date farming and contemporary production

The date palm is an iconic symbol of desert life (Brouk and Fishman, 2016) (Figure 1). The date palm can withstand the hyper-arid environments of the desert because of its ability to tolerate extremely high temperatures, saline soil and water conditions, and severe droughts. Richards (1954) considered that the date palm was the most salt tolerant of any fruit crop. Therefore, it is one of the most important plants of the desert (Zohary and Hopf, 2000). The date palm delivers multiple ecosystem services to desert-oasis landscapes by providing nutritional, economic, social, religious, and heritage values (Zekri et al., 2010; Aly and El-Hewiety, 2011). It has been considered that "... had the date palm not existed, the expansion of the human race into hot and barren parts of the 'Old World' would have been much more restricted" (Barreveld, 1993). Brouk and Fishman (2016) considered that the date palm is "... one of the oldest trees from which man has derived benefit and it has been cultivated since ancient times". One adage has it that the date palm "... has its feet in running water and its head in the fire of the sky".

Today, the top six date producing countries are, according to the Food and Agriculture Organization of the United Nations (FAO, 2017), in declining order: Egypt, Iran, Algeria, Saudi Arabia, Pakistan, and the UAE. Groundwater is mainly used to irrigate date palms in these hyper-arid and arid climes (Zaid and Arias-Jimenez, 2002), yet groundwater resources are under great pressure in these Middle Eastern, South Asian and North African countries.

Dates, water resources, and irrigation practices in the UAE

Rashoud (2016) suggested that the connection between the people of the UAE and the date palm is deeply rooted in the ancient past. In 2006, five Omani *aflaj* were granted UNESCO World Heritage Site status. These, and other

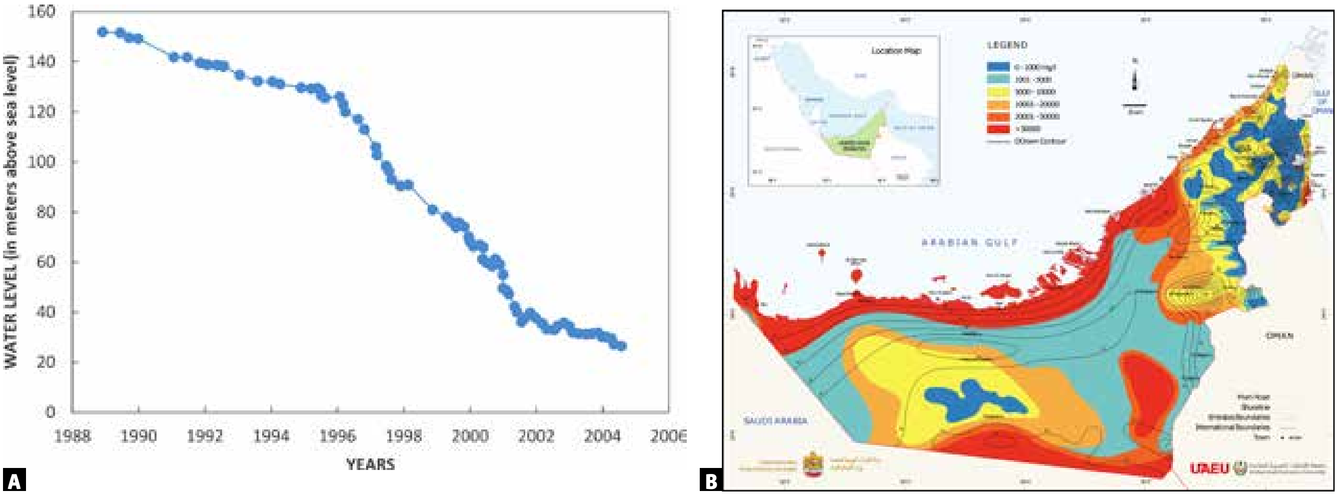

Figure 2. A. In the so-called ‘red-zone’ surrounding Al Ain, there has been over 100 m of decline in the groundwater level. B. A contour isoline map of the decline in the depth to groundwater in metres in the United Arab Emirates, along with the increases in the salinity of the underlying aquifers in mg L^{-1} between 1969 and 2012 (colour coded). Source: MOEW (2014). Reproduced with the permission of the Ministry of Climate Change and Environment (MOCCAE) and the United Arab Emirates University (UAEU).

aflaj, may date back to 500 CE (Common Era). Although archaeological evidence suggests that such irrigation systems may have existed on the Arabian Peninsula as early as 2500 BCE (Before Common Era). Yet Rashoud (2016) asserts that the strength of the bond between this ‘blessed’ tree and Emiratis remains ever strong today. The UAE has more than 40 million date trees, with over 200 cultivars, and nearly 70 of these are of commercial importance (Jaradat and Zaid, 2004). Modern drip and bubbler systems are used to supply pumped-groundwater to the individual basins around the date-palm trees (Figure 1).

Irrigation of date palms accounts for nearly one-third of groundwater withdrawals in the UAE (MOEW, 2015). Wada et al. (2012) calculated that 64% of the total irrigation demand in the UAE comes from non-renewable groundwater resources. There are grave concerns about the rapidly declining levels of groundwater tables in the UAE, especially in the Al Ain region of eastern Abu Dhabi (Figure 2A). In addition, the salinity of the remaining groundwater reserves is rising (Figure 2B). This rise in groundwater salinity is of concern, for Zekri et al. (2010) found that in Oman when the salinity of groundwater used for irrigation rose from an electrical conductivity of 5 to 15 dS m^{-1}, the gross economic margin of date production dropped by one-third. In 2017, in response to these burgeoning concerns about groundwater quantity and quality, Environment Agency – Abu Dhabi (EAD) announced the new Law 5 (2016), on the “Regulation of Groundwater in the Emirate of Abu Dhabi” (Figure 3). Law 5, which has come into force, asserts that the Government of Abu Dhabi owns the groundwater resource. In addition, Law 5 requires extraction limits be set for groundwater usage according to the proposed crop for which the water will be used to irrigate.

Under the auspices of EAD, we have completed four years of research on the water use of date palms to enable development of practical advice to growers on the sustainable use of saline groundwater to irrigate dates (Figure 4). We have also provided the requisite institutional and regulatory aspects of irrigation of date palms.

Here, we provide an overview of our Emirati research and present the key findings. The scientific details of this research have been published in Al-Yamani et al. (2017), Al-Muaini et al. (2018), and Al-Muaini et al. (2019a, b, c, d). The present review focuses on this work in the UAE only. However, in the aforementioned papers, we reference other international research on the water use of dates and, for completeness, we cite these here: Chao and Kreuger (2007), Madurapperuma et al. (2009), Roupsard et al. (2006), Sellami and Sifaoui (2003), Smith (1989), Sperling et al. (2012, 2014), Tripler et al. (2011), and Zhen et al. (2019).

Measuring and predicting palm-tree water use

The experiments we are reviewing here were carried out during 2014-2017 at the International Center for Biosaline Agriculture (ICBA) (25.09°N, 55.39°E, 48 m a.s.l.) near the city of Dubai. The ICBA date trial originally commenced in 2001 and 2002 and considered 18 cultivars. The 18 cultivars encompassed a wide range of tolerances to salt. Our detailed water-use studies considered the salt-tolerant ‘Lulu’, an Emirati cultivar (Figures 1 and 4), as well as the moderately salt-tolerant ‘Khalas’ from Saudi Arabia, and the salt-intolerant ‘Shahlah’ from the UAE. The ICBA trial considers three rates of irrigation water salinity: Block S1 = 5, S2 = 10 and S3 = 15 dS m^{-1}. Over four years, the hourly pattern of tree water use, ETc (L h^{-1}), was measured using the

Figure 3. Law 5 of 2016 concerning the “Regulation of Groundwater in the Emirate of Abu Dhabi”. The objective of this law is the management of groundwater in the Emirate (in Arabic).

compensation heat pulse method (CPHM) in just the two treatments S1 and S3 for each of the three cultivars. Details of the use of the CPHM in date palms have been described by Al-Muaini et al. (2019a). All the date palms were planted on an 8×8 m grid spacing. This enabled the daily water-use totals in L d^{-1} to be converted to units of mm d^{-1}, as required.

A weather station located at ICBA was used to estimate hourly and daily values of the reference evapotranspiration (ETo) using the standard FAO-56 approach (Allen et al., 1998). The transpiration of the date palms is related to ET_0 through the dimensionless crop factor, Kc, as follows: $ETc = Kc * ETo$, where ETc is the crop water use (L d^{-1}) and Kc is determined

Table 1. The effect of two rates of irrigation-water salinity on the annual tree water use (*ETc*), light interception (*LI*), and the crop factor (*Kc*) of three date cultivars at the International Center for Biosaline Agriculture (ICBA) near Dubai, United Arab Emirates. Also given are the respective ratios of *Kc*/*LI* (adapted from Al-Muaini et al., 2019b).

Cultivar	Irrigation salinity (dS m^{-1})	Annual ETc (kL year^{-1} tree^{-1})	Light interception (LI)	Crop factor (Kc)	Ratio Kc/LI
Lulu	5	50.0	0.26	0.31	1.19
	15	28.4	0.20	0.17	0.85
Khalas	5	43.1	0.31	0.26	0.84
	15	23.2	0.19	0.14	0.74
Shahlah	5	57.3	0.34	0.35	1.03
	15	31.1	0.18	0.19	1.06
Average					0.95

from the ratio of the measured daily sap flow to the reference *ETo*. In the UAE, the annual *ETo* exceeds 2000 mm year^{-1}, whereas average annual rainfall (*RF*) is just 50 mm year^{-1}. The climate is classified as hyper-arid since *RF*/*ETo* is less than 2.5%.

Our measurements of *ETc* and *ETo* enabled us to compute the daily pattern of *Kc* over several years for the three cultivars and the two rates of irrigation-water salinity. In Figure 5, we show how we found that the crop factor for the 'Lulu' S1 palms was 0.3.

The annual *ETc* and *Kc* results are given in Table 1, for all three cultivars across the two salinities of the S1 and S3 treatments. The palm-tree water use, *ETc*, ranged from 57.3 kL year^{-1} tree^{-1} ('Shahlah', S1) down to 23.2 kL year^{-1} tree^{-1} ('Khalas', S3). The crop factors, *Kc*, spanned the range from 0.35 down to 0.14 for these trees, respectively.

Table 1 reveals the complex effect of irrigation-water salinity and cultivar salt-tolerance on the water use of date palm trees.

The average yield of the S3 palms was 37 kg dates tree^{-1}, whereas the S1 trees yielded 74 kg tree^{-1}.

Matching irrigation to palm-tree water use

The challenge is to use this knowledge of these complex interactions to develop a policy recommendation for irrigation allocation that can be used in Abu Dhabi's Law 5.

We focused on the leaf area of the canopy, the prime driver of *ETc*, to develop a recommendation for Law 5. The rate and amount of water a palm-tree uses, under given ambient atmospheric conditions, is critically dependent on the leaf area of the palm-tree's canopy (Table 1). As a result of our observations of soil salinity conditions in the rootzone of irrigated date palm trees (Al-Muaini et al., 2019a, c), we considered that irrigation at the rate of 1.5 *ETc* would ensure sustainability. We considered this ratio of 1.5 would account for a 25% factor-of-safety, plus a 25% salt-leaching fraction. We found the 50% add-on to be sufficient to ensure that the saline groundwater used for 'today's' irrigation flushed out the excess salts left after the palm tree had osmotically removed 'fresh' water from the soil on the previous day to sustain its growth. Our results came from the ICBA trial at an 8×8 m spacing. Not surprisingly, not all date farms in the UAE have trees at this spacing, and nor do they use the same pruning protocols for canopy management. Therefore, we needed to be able to extrapolate our 'research plot' findings to cover 'commercial farms'. To do this, we re-focused our research on improved measurement of the trees' canopy area. The key, we thought, was an ability to measure the projected shadow area the canopies cast on the soil surface. We developed a 'light stick' for this, which is a bar about 1 m long with 20 PAR (photosynthetically active radia-

Figure 4. Dr. Ahmed Al-Muaini downloading data from the instrumented 'Lulu' date palms of the low salinity treatment (5 dS m^{-1}) at the International Center for Biosaline Agriculture near the city of Dubai, United Arab Emirates.

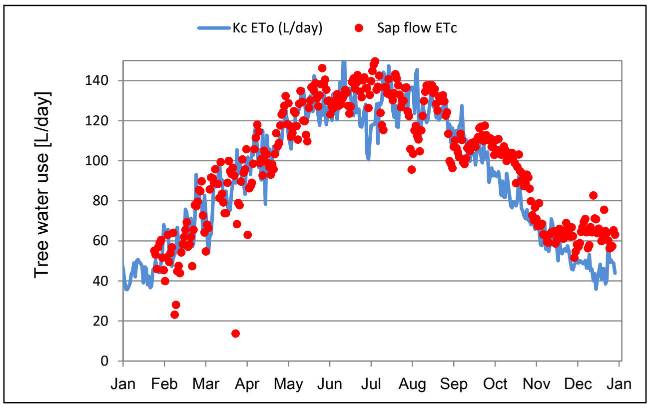

Figure 5. The average, measured daily tree water use, *ETc* (L d^{-1}) of three date palm trees (*Phoenix dactylifera* 'Lulu') at the International Center for Biosaline Agriculture near the city of Dubai, United Arab Emirates, as measured by the compensation heat-pulse method (red dots) over the full year 2014 for treatment S1 (5 dS m^{-1}). The model predictions are the calculation from the FAO-56 method, *ETc* = *Kc* * *ETo*, using the daily reference evapotranspiration *ETo* (L d^{-1}) and a crop factor *Kc* of 0.3. The three low daily values in February and April were rainy days. The dips in the measured *ETc* during early August and early September were because of problems with the operation of the irrigation system.

Figure 6. The light stick being used to measure the light interception fraction (*LI*) of the cultivar 'Shahlah' under the high salinity treatment S3 (15 dS m^{-1}). The light stick is 1 m long and comprises 20 equi-spaced quantum sensors that record photosynthetically active radiation at 2 Hz.

tion) sensors along it (Figure 6).

From the light stick, through multiple transects, we could calculate the light interception, *LI* (-), by the trees' canopies (Al-Muaini et al., 2019b). These *LI* results for our ICBA experiments are given in Table 1, and reflect the effect of both soil salinity and cultivar tolerance. The data range from 0.34 ('Shahlah', S1) down to 0.18 ('Shahlah', S3) as salinity and salt tolerance control canopy leaf area.

Goodwin et al. (2015) found that the ratio of *Kc* to *LI* was 1.2-1.3 for temperate fruit crops, such as apples and pears. However, for the salt-tolerant and drought-resistant palm trees here, we found the ratio, *Kc/LI*, to be just 0.95 (Table 1).

The challenge was then to extend these *Kc/LI* ratio results to the more than 110,000 commercial date farms in Abu Dhabi. One option would be to embark on a campaign to quantify, using the light stick, the canopy characteristics of palm-tree canopies on commercial farms. But we needed to simplify this even further.

Using Google Earth Pro™ we were able to link the fractional ground cover (*FGC*) of date-palm images to *LI* across 10 commercial farms (Figure 7) and our ICBA experiments. We found that the *Kc* value could be linked to *FGC*, such that $Kc = 0.78\ FGC - 0.08$.

Using Google Earth Pro™, we could predict the *ETc* of date palms on the 10 commercial date-palm farms near Al Ain, and along the Liwa Oases. The probability distribution function of the water-use values is shown in Figure 8. With high-density plantings and only moderate pruning strategies, the *FGC* can approach unity, or full canopy cover. Under these conditions, the tree water-use *ETc* can exceed 100 kL $year^{-1}$.

The regulated water allocation of Law 5 should then be 1.5 *ETc*, although there needs to be encouragement to develop pruning practices to reduce canopy leaf area, without reducing date yields.

As a final stage of this project, we considered the benefits and implications of using solar-powered desalination units (Burn et al., 2015; Dawoud, 2017) to dilute the saline groundwater being used for the irrigation of date palms. We found the cost of using this process to dilute 15 dS m^{-1} groundwater to 5 dS m^{-1} irrigation water was UAE dirhams (Dhs) 275 $tree^{-1}$ (1 Dhs = US\$0.27 in September, 2019). The yield benefit was 38 kg $tree^{-1}$ between the 15 and 5 dS m^{-1} salinities (Al-Muaini et al., 2019c). At Dhs 10 kg^{-1} for the price of dates, this means that the benefit-cost ratio of using desalinated water is 1.4. A valuable economic proposition. So the economic, cultural and heritage value of producing dates could be sustained using solar-powered desalination units.

However, this avoids the environmental concerns about the fate of the reject brine from desalination units in inland desert areas. Solutions for the use and disposal of the reject brine need to be found.

Future options

There are future opportunities for maintaining the production of dates in the hyper-arid deserts of Abu Dhabi. These involve the use of new technologies and novel economic opportunities involving desalination of brackish groundwaters. Simple benefit-cost assessments seem to suggest that the use of solar-powered desalination may be worthwhile.

Nonetheless, there must be sustainable solutions found for safe disposal of the reject brines that this solution offers. The opportunities created through the use of highly treated municipal-sewage effluents to augment the irrigation with groundwater of date palms must also be addressed. Critically, this will require socio-cultural assessments of the sustainability of using treated waste-waters to produce food of cultural, heritage and religious significance. There are many opportunities, and many threats, to the sustainability of date production in the hyper-arid and arid regions of the Middle East, South Asia and North Africa.

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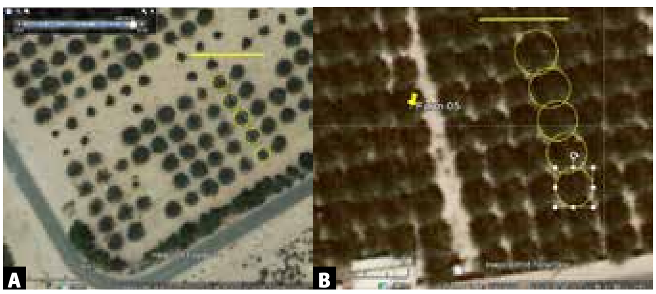

Figure 7. A. Google Earth image of part of the plantation of dates at the International Center for Biosaline Agriculture at which our experiments were carried out. The encircled trees are of the cultivar 'Shahlah' under the treatment S3 (15 dS m^{-1}). B. Google Earth image of a commercial date farm from the Liwa Oases. The circles show the approximate outlines of the trees' projected canopy areas. The yellow bar is a scale representing 28 m. The GIS image database was used to infer the fractional ground cover for these, and other farms.

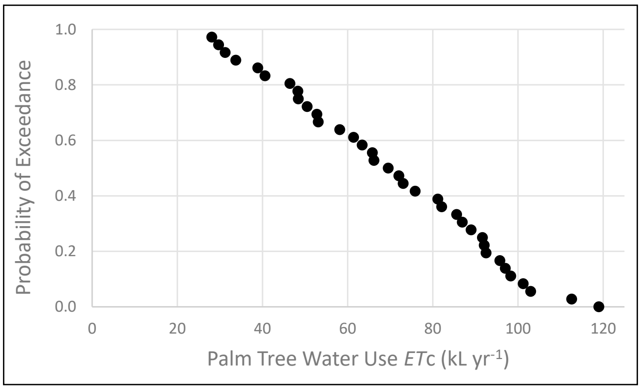

Figure 8. The probability distribution function of tree water use, *ETc* (kL $year^{-1}$) calculated for a wide range of date palms from 10 commercial farms in the Emirate of Abu Dhabi. The annual tree water use has been calculated using daily climate data for the reference evapotranspiration, *ETo* (mm d^{-1}), combined with a crop coefficient, *Kc*, as estimated from *LI* is light interception fraction being predicted from the fractional ground cover (*FGC*), determined from satellite imagery (modified from Al-Muaini et al., 2019d).

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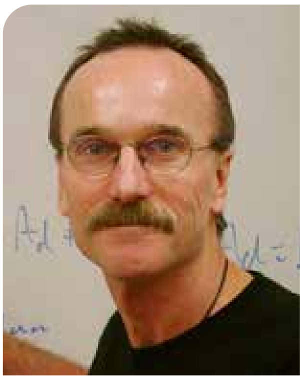
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› Courses and meetings

The following are non-ISHS events. Be sure to check out the Calendar of ISHS Events for an extensive listing of all ISHS meetings. For updated information, log on to www.ishs.org/calendar

Advanced Course on Statistical Tools for Plant Phenomic Data Analysis, 20-24 January 2020, Zaragoza, Spain. Info: Mediterranean Agronomic Institute of Zaragoza (IAMZ) – CIHEAM, Avenida de Montañana 1005, 50059 Zaragoza, Spain, phone: +34 976 716000, fax: +34 976 716001, e-mail: iamz@iamz.ciheam.org, web: www.iamz.ciheam.org

V International On-line Course on Postharvest & Fresh-Cut Technologies, 1 February – 30 September 2020. Info: Dr. Francisco Artés-Hernández, Postharvest & Refrigeration Group, Universidad Politécnica de Cartagena, Paseo Alfonso XIII, 48, 30203 Cartagena, Murcia, Spain, e-mail: postharvest@upct.es, web: www.upct.es/gpostref/

Advanced Course on Use of Sensors in Precision Agriculture, 3-8 February 2020, Zaragoza, Spain. Info: Mediterranean Agronomic Institute of Zaragoza (IAMZ) – CIHEAM, Avenida de Montañana 1005, 50059 Zaragoza, Spain, phone: +34 976 716000, fax: +34 976 716001, e-mail: iamz@iamz.ciheam.org, web: www.iamz.ciheam.org

International Horticulture Conference, 26-28 February 2020, Lahore, Pakistan. Info: Dr. M. Shafiq, phone: +923006561997, e-mail: ihc.2020@pu.edu.pk, web: http://www.pshsciences.org/events/

Advanced Course on Technological Innovation for Intensive Greenhouse Production, 9-13 March 2020, Almería, Spain. Info: Mediterranean Agronomic Institute of Zaragoza (IAMZ) – CIHEAM, Avenida de Montañana 1005, 50059 Zaragoza, Spain, phone: +34 976 716000, fax: +34 976 716001, e-mail: iamz@iamz.ciheam.org, web: www.iamz.ciheam.org

Advanced Course on Greenhouse Gas Assessment and Mitigation in Agriculture: Concepts, Methods and Simulation Tools, 30 March to 3 April 2020, Zaragoza, Spain. Info: Mediterranean Agronomic Institute of Zaragoza (IAMZ) – CIHEAM, Avenida de Montañana 1005, 50059 Zaragoza, Spain, phone: +34 976 716000, fax: +34 976 716001, e-mail: iamz@iamz.ciheam.org, web: www.iamz.ciheam.org

X Rosaceae Genomics Conference, 31 March - 3 April 2020, Barcelona, Spain. Info: Pere Arús & Amparo Monfort, IRTA (Institute for Food and Agriculture Research and Technology), Centre for Research in Agricultural Genomics (CRAG), CSIC-IRTA-UAB-UB, Edifici CRAG - Campus UAB, 08193 Cerdanyola del Vallès, Barcelona, Spain, phone: +34 932212242, e-mail: ariadna@geyseco.es, web: http://rosaceaegenomics.com/

XVI International Peatland Congress, 14-20 June 2020, Tallinn, Estonia. Info: Estonian Peat Association, e-mail: info@ipc2020.com, web: https://www.ipc2020.com/