Halophyte Use and Cultivation

Ricardo Radulovich and Schery Umanzor

Contents

Abstract

Considering that most of the water in the world is saline (i.e., by far mainly seawater), and that existing abundant salinized land areas and aquifers of the world are under limited or no use, including the vast sea surface, there is relevance and perhaps urgency in better use of saline environments for controlled plant production. Coupled to this, the existence of a substantial number of halophyte species, varying from herbs and grasses to trees, many of which have demonstrated economic usefulness, comes to complement the perspective of using these saline resources for agriculture- and forestry-like activities. However, and despite the abundant experimental data of cultivation irrigated with highly saline water or seawater, developed mainly through small-scale experiments, to date there are no halophytes as major crops nor truly commercial-scale cultivation activities. The main limitations identified to advance halophyte "cash crop" cultivation were problems related to irrigation with highly saline water and partial or no significant domestication of species and variants used, coupled to inadequate technology for production, harvesting, and post-harvest processing of products. However, and notwithstanding work that must continue towards that

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end, other cultivation or controlled-production possibilities are discussed, which may more readily advance the application of halophytes to different situations. The domestication of halophytes to substitute glycophytes in moderately saline conditions is supported as a valuable alternative. Additionally, the ecosystem and biodiversity services rendered by implementing controlled halophyte plantings, e.g., mangrove replanting or land reclamation, are considered of relevance. Finally, a halophyte agroforestry perspective is proposed as a tool to advance this strategy.

Keywords

Seawater · Irrigation · Halophyte agroforestry · Mangroves · Food

1 Introduction

Earth is largely saline on its surface. The oceans cover about 71% of the planet and hold 97% of the water. On land, although recent data are lacking, around 1 billion hectares (ca. 7% of the land surface) are covered with saline soils, often with corresponding saline aquifers (Greene et al. 2016; Zaman et al. 2018). In addition to soil and aquifer salinization from agriculture irrigation, sea level rise, which may exceed 1 m by 2100 (Horton 2020) will flood extensive coastal lands (Flowers and Muscolo 2015) and, through seawater intrusion related to overexploitation, salinize coastal aquifers (Fienen and Arshad 2016). In the context of ongoing global land and water exhaustion and degradation, fostered by climate change and unsatisfied yet increasing demand for food and related products, salinity issues of land and water gain preponderance, both as problems and opportunities. In the front line of these are halophytes.

Water supply, for its many uses but particularly for both rain-fed and irrigated agriculture, is largely affected by depletion and pollution of natural and man-made reserves and by increases in rainfall variability and extreme climatic events like droughts and heat waves (IPCC 2013; Raymond et al. 2020). The relationship between water and agriculture, or rather the extreme dependency of agriculture on water, is evidenced when considering that a crop in a sunny day evapotranspires (i.e., consumes from the soil) in the order of 5 mm d^{-1} or 50,000 L water ha^{-1} d^{-1} (FAO 1998). Because of this, 20% of the global agricultural land under irrigation consumes 70% of the world's available freshwater (Steduto et al. 2012, Du et al. 2015), while rain-fed agriculture is growingly affected by increasing rainfall variability and droughts brought about by climate change.

On the other hand, adequate land for agriculture is dwindling. This is evidenced by continued tropical deforestation, which between 2010 and 2015 was of 5 million hectares per year in humid tropical Africa and South America, mainly to establish new land for agriculture and ranching (FAO 2016), and by land grabbing, which has been more adequately termed water grabbing as it happens in areas well provided with rainfall (Dell'Angelo et al. 2018). It is projected that needed increases in food production, conservatively estimated at 70% from 2005 to 2050 (FAO 2011), will have to come mostly from increasing productivity on existing land and only 10% from increasing land area for agriculture (OECD-FAO 2018). Water is the main limitation to increasing agricultural productivity and to placing extensive dryland areas into production.

Considering that most of the water in the world is saline, i.e., by far mainly seawater, and existing abundant salinized land areas and aquifers of the world are under limited or no use, including the vast sea surface, there is relevance and perhaps urgency in the better use of saline environments for agriculture. Coupled to this, the existence of a substantial number of halophyte species, varying from herbs and grasses to trees, many of which have demonstrated economic usefulness, comes to complement the perspective of using these saline resources for agriculture- and forestry-like activities.

In this chapter, first the current and potential uses of halophytes, particularly in highly saline contexts, are presented and discussed in relation to global and local conditions. The use of halophytes is analyzed not only regarding products that can be obtained from their biomass but also concerning ecosystem services, such as replanting mangrove forests for coastal protection and reclaiming salinized lands using halophytes.

After that, the main possibilities for cultivating halophytes using saline water, again particularly seawater, are presented but also considering their potential role in substituting glycophytes in lesser saline environments. Opportunities and limitations are analyzed based on existing experience while positing some new or less-explored possibilities. These are presented and discussed in relation to growing water limitations for conventional agriculture and the advantages and complexities associated with using saline water for controlled plant biomass production.

Finally, perspectives for the future are posited based on a prioritization scheme that favors the most immediately implementable of the activities with halophytes, relegating to a second plane those that require research and technology development, as well as crop selection and improvement in the context of domestication. In this sense, there are several if not many productive activities that can be implemented utilizing halophytes as they exist right now and as we know them. This represents not only an immediate contribution to the world's plant biomass production capacity and environmental needs, but it also may help open the door to expanding these applications as both better crops and viable production possibilities are consolidated.

2 Halophyte Use and Cultivation

Halophytes, broadly defined as plants that grow well in saline environments (e.g., Grigore and Toma 2017), yet also as extremophiles that tolerate salinities toxic to most plants (e.g., Flowers and Muscolo 2015), are a broad and varied group of plants found worldwide. From small herbaceous plants to succulents and seagrasses to sizable mangrove, coastal, and leguminous trees, halophytes are found from dry and saline soils to marshes to shallow sea bottoms. They also range from seagrasses and, extending the definition, seaweeds growing fully submerged at shallow sea bottoms to xerohalophytes which grow in saline soils in dryland conditions.

Although estimating the number of halophyte species is difficult, because often no clear distinctions are made between salt-tolerant and halophytic species, particularly euhalophytes (Yensen and Biel 2006), halophytes represent at most 2% of terrestrial plant species (Glenn and Brown 1999; Flowers and Colmer 2008; Panta et al. 2014). Others, however, have narrowed this list to 1560 spp. in HALOPH (Aronson 1989), ca. 1500 spp. in eHALOPH (Santos et al. 2016), and to >2500 spp. (Menzel and Lieth 2003), making true halophytes less than 1%, rather closer to 0.5%, of the accepted species names of flowering plants found in http://www.theplantlist.org/. Still, variation is considerable, with 24 families of flowering plants containing 75% of spp. in the eHALOPH database, with Amaranthaceae leading with 353 spp., followed by Poaceae (120), Leguminosae (77), and Compositae (60) (Santos et al. Santos et al. 2016).

Thus, with ca. 2000 spp. belonging to dozens of families distributed around the world in differing ecosystems, halophytes offer a broad menu of possibilities for their use beyond traditional, local, and natural vegetation uses. Meanwhile many of their uses and applications are unexplored and remain to be known, documented, or even properly advanced. Many halophytes have different uses that make them valuable in their natural environments, both for products and ecosystem services (Eganathan et al. 2006; Weber et al. 2007; Koyro et al. 2011; Tug and Yaprak 2017).

Excepting some glycophytic crop species or variants that can tolerate salinity and for which there is growing interest in their salt tolerance, such as facultative halophytes quinoa (*Chenopodium quinoa*) (Adolf et al. 2013), pearl millet (*Pennisetum glaucum*) (Panta et al. 2014), and sunflower (*Helianthus annuus*) hybrids (Karrenberg et al. 2006), there is no halophyte classified among the major or widely utilized crops of the world. More so if we were to consider them as such while being grown in highly saline conditions. This may be because glycophytes, i.e., for the sake of argument the rest of the plants that are not halophytes, offer a broader range of possibilities. Glycophytes are over 150 times more diverse than halophytes, many have faster growth rates, and are found in the environments where people evolved (i.e., not saline). In that sense, halophytes for which uses are known or have been demonstrated, mainly as local and niche crops, can be considered in the category of neglected or underutilized crops (e.g., Mayes et al. 2012; Mabhaudhi et al. 2017).

Nonetheless, there is an abundant and growing body of information and knowledge on halophytes, which is materialized in a large number of papers, books, and chapters on the subject – ranging from the physiological and evolutionary perspective (e.g., Cheeseman 2015) to a plethora of listings, uses, and applications, often around the "cash crop" and biodiversity concepts (e.g., Glenn and Brown 1999; Joshi and Khot 2004; Khan and Weber 2008; Ventura and Sagi 2013; Khan et al. 2014; Teixeira et al. 2014; Ventura et al. 2015; Loconsole et al. 2019). Additionally, there are plant databases dedicated to halophytes partially or entirely, as is eHALOPH (Santos et al. 2016), which evolved from HALOPH (Aronson 1989). (Halophytes are listed and often described and referenced in several active plant databases. Among them: The Plant List (http://www.theplantlist.org/); the Purdue University Center for New Crops and Plant Products (https://hort.purdue.edu/newcrop/Indices/index_ab.html#A); the Biosalinity Awareness Project, where a listing of other online databases and listings is provided (http://www.biosalinity.org/salt-tolerant_plants.htm#Salinity_Thresholds); and, more specifically, the halophytes database eHALOPH (https://www.sussex.ac.uk/affiliates/halophytes/); also see Santos et al. (2016).) This interest in halophytes is perhaps due to the severe problems related to water shortages and salinity for which halophytes, probably rightly so, offer solutions. The fact that halophytes have different mechanisms to deal with excess salts makes them valuable subjects of biological study (e.g., Parida and Das 2005; Karrenberg et al. 2006; Sobhanian et al. 2011).

In spite of millennia of local and traditional uses of halophytes around the world, and a decades-long interest in advancing their cultivation (Boyko and Boyko 1959; Boyko 1966; Glenn and Brown 1999), to this moment there are no known implementations of halophyte farming of any significant scale around the world. Despite myriad small-scale experimentation, often with different methodologies and conceptualization of salinity levels (e.g., different levels of water salinity are used indistinctively), the state of the art has lead different authors to conclude that "introducing non-domesticated halophytic plant species as agricultural crops with reasonable income for the growers will require the refinement of growing protocols and selection of improved varieties" (Ventura et al. 2015) and "although studies proclaiming the promise of halophyte agriculture are reasonably well represented in the international scientific literature, reports of their local, small scale but successful implementations are not" (Cheeseman 2015). Additionally, Joshi et al. (2015) stated that "Despite considerable progress... There is still a lot to characterize about halophytes...."

Yet existing knowledge and advancements to date, when placed under a light broader than the quest for "cash crops" reinforcing large-scale agriculture, allow to believe that, notwithstanding the irrigated row-crop concept, there are many valuable applications ready to be implemented or close to be, perhaps after screening procedures (e.g., Aronson et al. 1988; Koyro et al. 2011). Most likely, thinking out of the box may represent the most valuable avenue to mainstream halophytes as part of a wide array of solutions to pressing problems, both related to biomass from cultivation or controlled planting and the ecosystem services this provides.

2.1 Halophyte Use

There is a long history of using halophytes for food, feed, and many other uses, mostly or traditionally in local contexts as they grow naturally (e.g., NRC 1990; Qasim et al. 2011; Mayes et al. 2012; Gunning 2016; Mabhaudhi et al. 2017). Yet it was not until the twentieth century that they were studied systematically (Flowers and Muscolo 2015). Since cultivation is mostly an ongoing research activity, which includes selection of species and variants, there are very few if any examples of commercial agriculture-like production of halophytes as crops. However, the richness of local uses, and the apparent potential to out-scale them, prompted an early and visionary report by the US National Research Council on the use of salt-tolerant plants for developing countries (NRC 1990).

The uses reported, as well as the halophyte species being considered, are ample and cover a similar spectrum as regular agricultural crops. As extracted from several key publications (e.g., Aronson 1985; NRC 1990; O'Leary et al. 1985; Glenn and Brown 1999; Koyro et al. 2011; Ventura et al. 2015), the primary reported uses or applications of halophytes are:

Products
Food (including traditional/local, famine, gourmet, and nutraceutical foods)
Animal feed and forage
Biofuel and fuelwood
Chemicals, medicinal uses, and industrial products
Other products, including lumber, fiber, and flowers

Services
Ornamentals and landscaping
Coastal reclamation and protection
Land reclamation and protection
Carbon sequestration
Biodiversity preservation and honey production
Bioremediation or phytoremediation

Notably, many or all services listed are transversal and can or should be implemented together with products sought. For example, replanting mangroves for controlled fuelwood extraction provides a host of services like coastal reclamation and protection, biodiversity preservation (including support of fisheries), bioremediation, and carbon sequestration. To consolidate applications of halophytes, and continuing with this example of mangrove replanting, it would be a matter of adding payment for ecosystem services to the direct economic benefits that can be obtained, in this case from controlled fuelwood extraction.

Halophyte use, both for products and services, has been described and characterized by many different authors. In Table 1, the major examples of the use and potential use of halophytes according to various authors, who in general agree perhaps with different levels of enthusiasm, are presented in general, for specific uses, and for specific species or groups, citing the corresponding source.

Regarding halophytes as food, the use of their seeds is considered an important application. Although halophytes accumulate high concentration of salt (ash) in their tissue, their seeds do not particularly accumulate more salt than glycophyte ones (O'Leary et al. 1985; NRC 1990; Glenn and Brown 1999; Glenn et al. 2013). Several studies have shown that halophyte seeds can store high concentrations of saturated and unsaturated fatty acids accounting for more than 20% of the total dry seed weight, in addition to proteins (Weber et al. 2007; Abideen et al. 2011). Although there are studies indicating moderate to high seed yields and of good oil quality in

Table 1 The major or representative examples of the use and potential use of halophytes, including general or different uses, specific uses, and uses for specific species or groups of spp.

Category	References
General, different uses	
Broad review of economic halophytes, including historic uses such as for barilla and rushes; the use of eelgrass (*Zostera marina*), a seagrass; as food staple; and the use of multipurpose trees in India	Aronson (1985)
Salt-tolerant plants for developing countries	NRC (1990)
Crop potential of halophytes as vegetable, forage, and oilseed crops	Glenn and Brown (1999), Glenn et al. (2013)
List 168 halophyte spp. that belong to 32 families which can be irrigated with seawater	Kefu and Hai (1999)
Book on saline management, several chapters on halophytes	Pessarakli (1999)
Book with chapter describing halophyte uses, including chapter for the twenty-first century, as staple crops, ornamentals, dune stabilizers, and environment-improving halophytes	Khan and Weber (2008), Yensen (2008)
Halophytes for different uses, including landscape and soil rehabilitation in the context of saline agriculture	Ladeiro (2012)
Sabkha Ecosystems book	Khan et al. (2014)
Halophytes as human food, for forages and animal feeds, energy crops, phytoremediation, medicinal plants, and other commercial products	Panta et al. (2014)
Halophytes for fodder, food and gourmet vegetables (several succulents with their tender shoots sold as samphire, including *Salicornia* sp., *Crithmum maritimum*, *Sarcocornia*, perhaps even *Sesuvium portulacastrum*), landscaping and ornamentals, multifunctional applications, industrial uses, and use in constructed wetlands for purification of marine aquaculture effluent. Also indicates antinutritional factors	Ventura and Sagi (2013), Ventura et al. (2015)
Halophytes for landscaping, as ornamentals, and for coastal protection, among other uses	El Shaer (2006)
Specific uses	
Halophytes as cash crops for animal feeds in arid and semi-arid regions; analyzed halophytes as forages, indicating limitations and the need to fortify with energy supplements (e.g., *Atriplex* is not good on itself due to low caloric content and must be supplemented)	El Shaer (2006), Norman et al. (2013), Ventura et al. (2015), Attia-Ismail (2018)
Analyzed halophytes as potential food source in Turkey	Tug and Yaprak (2017)

(continued)

Table 1 (continued)

Category	References
Through a more botanical and physiological focus, including breeding approaches and comparison to glycophytes, analyzed the potential of halophytes as crops	Joshi et al. (2015)
Following a similar approach as above, described a host of halophytes as crops and the need to improve their individual crop potential	Koyro et al. (2014)
Analyzed the potential of halophytes as bioenergy crops	Sharma et al. (2016)
Analyzed halophytes as floricultural crops	Cassaniti et al. (2013)
Flowering halophytes for honey production	NRC (1990), Ventura et al. (2015)
Medicinal uses: Reviewed 45 coastal and near-coastal species from Pakistan traditionally used as medicine for seven different types of disease conditions	Qasim et al. (2011)
Analyzed halophyte species as sources of bioactive substances, antioxidants, nutraceuticals	Ksouri et al. (2012), Boestfleisch et al. (2014)
Analyzed fatty acid composition of 19 Mediterranean halophytes	Vizetto Duarte et al. (2019)
Considered biofiltering of aquaculture effluents by halophytic plants	Buhmann and Papenbrock (2013)
Analyzed halophytes for phytoremediation, regarding salinity and heavy metals	Manousaki and Kalogerakis (2011), Lutts and Lefevre (2015)
Considered halophytes for wood, *Tamarix* spp. and mangroves	El Shaer (2006)
Uses for individual species or group of spp.	
Crithmum maritimum, a halophyte naturally found on the rocky coastlines of the Atlantic Ocean and the Mediterranean Sea, has a long history of human consumption and was recently suggested as a cash crop for biosaline agriculture	Ventura et al. (2014)
Salicornia spp. Members of the Salicornioideae are promising candidates for saline agriculture due to their high tolerance to salinity. Analyze both Salicornia and Sarcocornia from the cultivation focus	Glenn and Brown (1999), Ventura and Sagi (2013), Singh et al. (2014)
Sesuvium portulacastrum or sea purslane is described as a halophyte used as a vegetable, fodder, ornamental plant, and for bioreclamation of saline soil and production of a secondary metabolite for the sericulture industry	Lokhande et al. (2009), (2013), Radulovich et al. (2017)
Analyzed the potential of using the common ice plant (*Mesembryanthemum crystallinum*) in both the wild and as a crop, indicating the	Loconsole et al. 2019

(continued)

Table 1 (continued)

Category	References
benefits of its antioxidant properties and mineral composition to human health	
Mangroves analyzed from different perspectives, emphasizing ecosystem services (mitigate erosion, coastal carbon sinks, relation with aquaculture and fisheries) but also products such as fruits and fuelwood from controlled harvests versus rates of deforestation	Kathiresan and Bingham (2001), El Shaer (2006), Duke et al. (2007), Laffoley and Grimsditch (2009), Suman (2019)
Sea grape, *Coccoloba uvifera*, fruits as sources of antioxidants	Segura Campos et al. 2015
Various halophyte trees and shrubs, e.g., *Conocarpus lancifolius*, planted directly in seaside quarries to produce fuel and fodder from otherwise useless land	Aronson (1985)

several experimental trials, even comparing its performance to conventional oilseeds, research on halophyte oilseeds is limited, partly due to problems related to harvesting (e.g., Weber et al. 2007; Glenn and Brown 1999; Glenn et al. 2013).

Concerning the high accumulation of salt in halophyte tissue, there are workaround solutions that can still allow the consumption of vegetative tissue. One technique consists of soaking plants in seawater directly after harvest. Another option is limiting consumption to young vegetative shoots, e.g., as occasional vegetables or gourmet foods such as Salicornia (Ventura et al. 2015) sold as samphire grass in England, or selecting halophyte species or varieties for low salt accumulation (Ventura et al. 2015) (It was a pleasant surprise to RR, when visiting early 2019 a Harrods' store in London, to find young shoots of samphire being sold for salads.). Halophytes may not only be nutritious but also contain bioactive substances including antioxidants and nutraceutical properties (Ksouri et al. 2012; Boestfleisch et al. 2014), and their application to medicine and the extraction of interesting metabolites are exemplified in Table 1. On the other hand, in addition to the accumulation of high value nutritional components, halophytes can also accumulate undesired compounds. Among these antinutritional factors are oxalates, nitrates, phenols, saponins,

tannins and salts, and high ash as well (Ventura et al. 2015). Once again, selecting for species or varieties with low concentrations of undesirable compounds is an option.

Other interesting uses are the use for animal feeds or fodder, with a recurrent commentary that halophyte biomass needs to be supplemented energetically; their potential use as crops for biofuel; the many applications to landscape reclamation, stabilization, and protection; the use of flowering halophytes for honey production; and a host of other uses (Table 1).

Although eHALOPH lists 44 aquatic halophytes and several are listed as seagrass, there is little information or even manifested interest in exploring applications or use of these species, save for the cite of eelgrass used as food in Table 1. Of course, protection of seagrass turfs is a common activity, particularly as these are threatened by ocean warming and heat waves, yet no example has been found of ongoing attempts to cultivate or even use products from seagrasses.

In contrast, although not formally defined as halophytes, seaweeds can add value to the halophyte issue. Already ca. 30 million tons of seaweed fresh biomass are produced yearly via cultivation (FAO 2018), most of it for food and hydrocolloid production which is commonly a food additive. Farming of seaweeds (e.g., Radulovich et al. 2015a) is a growing activity and may eventually be related to other aquatic halophyte production in a manner integrated with trophic-smart mariculture and fisheries and a variety of ecosystem services (e.g., see a biodiversity enrichment effect from cultivated seaweed plots, Radulovich et al. 2015b).

To consider seaweeds together with halophytes is relevant not only because they share saline media but also because their biomass carries similar high salt and ash content as halophytes, and there may well be other similarities as well. Indeed, a comparative analysis of mechanisms to cope with excess salt and the resulting metabolism between halophytes and seaweeds is lacking.

2.2 Halophyte Cultivation

As indicated earlier, in a decades-long interest (Boyko and Boyko 1959; Boyko 1966; Aronson et al. 1988; NRC 1990; Glenn and Brown 1999) that has not generated sufficient traction to date, halophytes have been, though mostly experimentally and at small scale, cultivated as agricultural crops with varying degrees of success, grown irrigated often but not always with highly saline waters up to the use of seawater – which is of most interest because of its abundance and ubiquity. (Seawater has on average 35 g of salt per kg, something that is reported as 35 parts per thousand (ppt) or, more recently, as 35 practical salinity units (PSU). In terms of electrical conductivity, that of seawater is around 55 dS m^{-1} or mS. To maintain the proper perspective on the widely varying salinity levels of water used for irrigation as reported in the literature is essential as is oftentimes confusing. For example, Boer (2008) stated that “It is especially important to focus on those halophytes that can tolerate full strength seawater salinity, such as sea grasses, marine algae, as well as those flowering plants that can produce biomass and reproduce while being continuously irrigated with seawater.”) However, as indicated by Ventura et al. (2015), the ideal halophyte crop for conventional agriculture with highly saline water has not yet been identified.

Nonetheless, as water grows scarce or its supply less dependable, affecting food production, the question of using halophytes as crops, in its broadest sense from irrigated row crops to replanting mangroves for natural regeneration, or even cultivating them at sea, is or should be back on the table. Yensen (2008) said halophytes and their use will be an essential topic in this century and that a potential may exist to develop as many as 250 halophyte staple crops. Several others (e.g., Glenn and Brown 1999; Flowers and Muscolo 2015) consider halophytes important in our ability to feed the human population, “aiding the transformation of current crops as well as providing new halophytic crops" (Flowers and Muscolo 2015). This cultivation potential of halophytes can be rain-fed where possible, irrigated where needed, or sea-fed in coastal and other aquatic production techniques.

Irrigating halophytes with highly saline water is not without problems. Given the high amounts of irrigation water needed, which with irrigation inefficiency plus a salt-leaching requirement (Richards 1954; Nielsen and Biggar 1961) can easily be of 100,000 L ha^{-1} day^{-1}, the handling of seawater or of high-salinity water for irrigation is challenging on itself – with corrosion being the first obstacle. Adding to the soil via irrigation with seawater (35 g salt L^{-1}), e.g., to near-coastal desert land, in the order of 3.5 MT of salt per hectare per day is quite a complication. Even when properly leaching these salts from the root zone via percolation with excess water, so they do not accumulate, and thus salinity is not allowed to increase to intolerable levels, the first question to answer is where is all that salt going. It may well be unacceptable in the long term, and it is perhaps one of the underlying reasons why this irrigated crop-production modality does not prosper, except at very small-scale experiments. As indicated earlier, land and aquifer salinization from irrigation is already a problem and that not even using seawater for irrigation.

Thus, the technical feasibility of successful halophyte cultivation through plantings at small scale during short periods may be considered incomplete given the dimension of the salt problem mentioned above. As indicated by Panta et al. (2014), "there is little doubt that the time has come for the use of halophytes in saline agriculture to move from the laboratory and small field trials to large-scale commercial production." A true proof of concept, in this case, would require an operation at a scale of several hectares during several years, tracking salts as they are leached from the root zone with excess irrigation. If, as stated above, 3.5 MT of salt per hectare per day are applied, a small 10 ha field irrigated during 200 days a year will add 7000 tons of salt per year that will be leached into the deeper soil, perhaps finding its way into groundwater or merely staying there until eventually a problem may generate.

Notwithstanding the difficulties that may be encountered when irrigating extensive land areas (e.g., coastal desert areas) cropped to halophytes with seawater, there is substantial – though mostly experimental – evidence that halophytes can be produced as crops fully irrigated with seawater. After the pioneering work of Boyko (Boyko and Boyko 1959; Boyko 1966), showing that halophytes can grow and yield when irrigated with seawater, many other works have consolidated this concept. For example, Aronson et al. (1988) tested 120 halophytes irrigated with seawater, reporting success for 78 of the species. Glenn and Brown (1999) tested a variety of halophyte species, concluding that "The most productive species yield 10 to 20 ton/ha of biomass on seawater irrigation, equivalent to conventional crops. The oilseed halophyte, *Salicornia bigelovii*, yields 2 t/ha of seed containing 28% oil and 31% protein, similar to soybean yield and seed quality." Kefu and Hai (1999) analyzed halophytes with known economic use that can be irrigated with seawater, indicating that 168 species that belong to 32 families are in this category.

Besides the problems of irrigating with seawater just discussed, other limitations that inhibit the commercial implementation of halophyte "cash crop" farming are related to seed germination problems in high salinity (Khan and Gul 2008; Ventura et al. 2015) and their high salt content, antinutritional compounds present in some species, and other limitations indicated in relation to Table 1.

In general terms, these crop-related problems may be entirely related to an incomplete domestication of wild halophytes that are placed into agricultural production at too-early a stage. Ventura et al. (2015) have indicated that "introducing non-domesticated halophytic plant species as agricultural crops with reasonable income for the growers will require the refinement of growing protocols and selection of improved varieties." On the issue of domestication as applied to glycophytes, Mayes et al. (2012) stated that "In the last century, the yield of seed from wheat and the yield of oil from oil palm have both quadrupled. Interestingly, this improvement can be attributed roughly equally to management/agronomy and genetic improvement in both crops."

Evidently the domestication processes, including, e.g., translating into a new breed of crops the knowledge and resources from halophyte relatives of crop plants through functional genomics (Joshi et al. 2015), coupled to technological advances for cropping, harvesting, and post-harvest processing, are critical elements to providing the world with "cash crop" halophytes that allow to break the cultural and economic inertia that may be inhibiting the advancement of halophyte agriculture. For this, concepts around marketing may be essential. For instance, establishing a demand-driven market may be key to develop halophyte agriculture within economic conditions, instead of, apparently, attempting to do it via supply-driven actions.

Nevertheless, particularly in times of climate crisis and growing land and freshwater limitations, lest we should never know what we are missing or how far we can get if we invest in it, we must confront dilemmas and explore the issue of halophyte cultivation and use. This, however, may require keeping an open mind to alternative modalities in highly saline water provision to crops. For the effective cultivation of halophytes using seawater, different methodologies to provide water may be needed. This may well mean different farming methodologies altogether, which can well be based on developing halophyte crops to substitute for glycophytes in moderately saline conditions (e.g., see Glenn and Brown 1999).

Meanwhile, advancing innovative or alternative cultivation strategies for specific conditions and multiple purposes can be achieved by several ways: coastal mangrove replanting for some fuelwood, plus the many ecosystem services from coastal restoration and protection; carbon sequestration, and enhancement of biodiversity and fisheries; planting halophyte trees and bushes to reclaim abandoned saline soils that benefit from sufficient rainfall to support growth and a low to medium product yield, which is compensated by the ecosystem services brought about by these plantings.

In this latter sense, but also related to promoting forest-like natural regeneration and phytoremediation of soils affected by salinity (see Manousaki and Kalogerakis 2011; Lokhande et al. 2013), halophyte agroforestry efforts (see example in Fig. 1) should be emphasized, combining agriculture-like objectives with more environmentally and biodiversity-related ones.

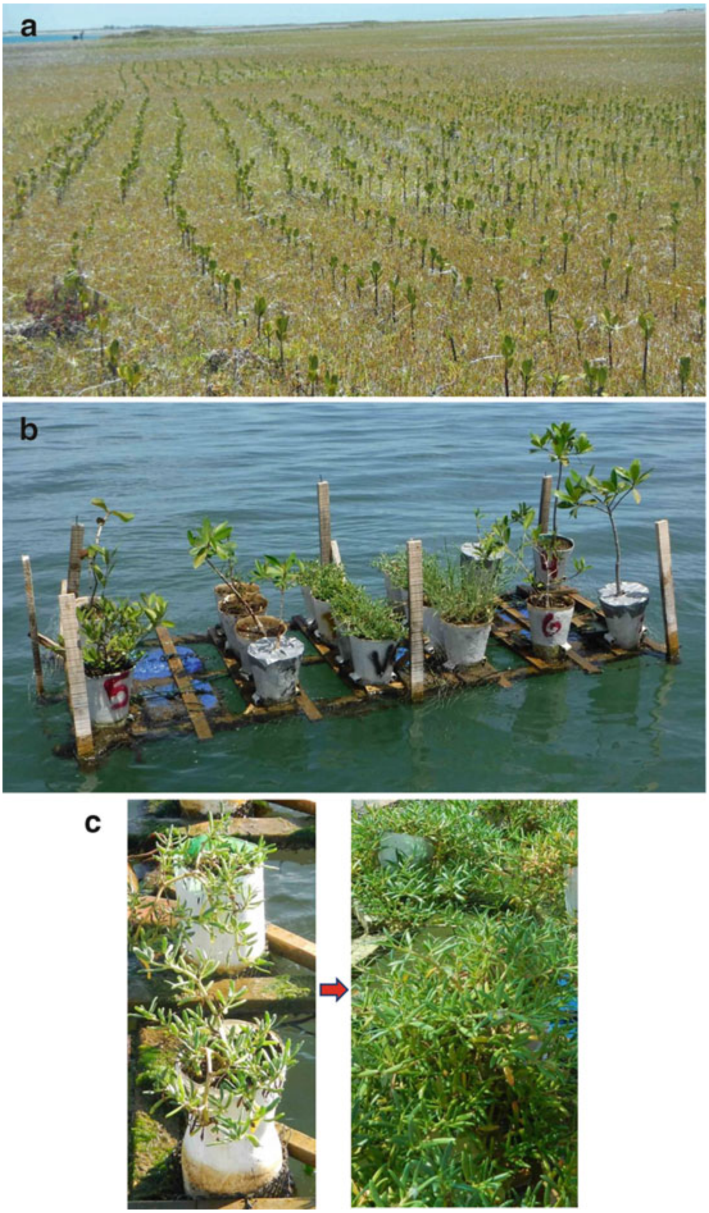

Fig. 1 (**a**) Planting of mangrove, *Rhizophora mangle*, in Sumatra. (Photo courtesy of Jorge Borbón Ramírez). (**b**) and (**c**) Floating halophyte production, Pacific waters, Costa Rica, showing floating barges in which potted halophytes of several species were grown for 2 years (Radulovich et al. Radulovich et al. 2017). Seawater was provided through holes at the submerged lower end of cone-like pots through capillary rise and wave action (bobbing), while rainfall through the rainy season also entered the pots through the open upper surfaces. In 1C the growth of sea purslane (*Sesuvium portulacastrum*) in ca. 1 month is shown

Innovative or alternative farming technologies or objectives are also emerging, including growing halophytes for biofuels, using them for bioremediation of mariculture pond waters, and even growing potted halophytes floating at sea, namely, sea purslane, salt couch grass, and two mangrove species, fully provided of water by seawater plus any rainfall (see Fig. 1, Radulovich et al. 2017). Additionally, the farming of seaweeds indicated above is another line of action that is growing and can be intimately related to halophyte production and use.

3 Conclusion

Traditional agriculture is growingly threatened by the decreasing availability of freshwater and adequate land. Saline agriculture with halophytes as crop is becoming a crucial research topic, not only for dry areas and those subject to soil and aquifer salinization but wherever the interface with the sea warrants it. Although there is an abundant body of knowledge and experience with halophyte use, this is mostly of a local or traditional nature that has been brought to a broader constituency mostly via literature and experimental work usually conducted at very small scale. Moreover, oftentimes this research is conducted with arbitrary levels of salinity in the water used for irrigation, making results difficult to collate for generalized purposes. To counteract this, the salinity of seawater is proposed here as the standard to which all experiments should refer to in determining the salinity levels they choose.

Halophytes and the existence of abundant saline water represent a valuable perspective that requires a continued thorough exploration. What if some or many halophytes can sustainably become high-yielding crops under seawater irrigation? Can this be a significant addition in global food production capabilities? Alternatively, can halophytic genes be transferred to crops that already tolerate some degrees of salinity, forging super halophytes that combine the best of both glycophytes and halophytes? Yet also many halophytes may be advanced as “cash crops” to substitute for glycophytes in moderately saline conditions.

To date, halophytes have demonstrated their importance for a wide range of applications ranging from food and feed production to phytoremediation of stressed environments and as support for aquaculture (Table 1). Clearly, many halophytes have economic use, be it through their products and/or through their ecosystem and biodiversity services, yet viable production systems of fully domesticated halophyte crops remain to be developed and scaled up.

The human-aided rapid evolution of teosinte into maize (Iltis 1983), the increases by over 400% in chicken growth obtained in the second half of the twentieth century (Zuidhof et al. 2014), and the quadrupling of yields from wheat and oil palm in the last century (Mayes et al. 2012) are examples of what could be achieved with further exploration into halophyte domestication. Interestingly, as indicated earlier, the dramatic improvements for wheat and oil palm can be “attributed roughly equally to management/agronomy and genetic improvement” (Mayes et al. 2012). When applying search and selection processes for neglected or underutilized crops (e.g., Mayes et al. 2012; Mabhaudhi et al. 2017), a plethora of opportunities may arise, of which many can be “ dramatically improved for yield, based on a strategic mix of improved management/agronomy and selective breeding” (Mayes et al. 2012). While the large-scale cultivation of halophytes irrigated with seawater or other highly saline waters seems to require considerable refinements, attempting to domesticate halophytes to substitute for glycophytes in moderately saline agriculture conditions is a worthy strategy that may yield results faster and more pertinently.

The same criteria can be applied to production systems that may require looking outside the box of conventional agriculture to advance this promising option. Cultivating the sea in a form analogous to what is being done with seaweeds may well be as promising a field to develop as it is cultivating halophytes on land irrigated with highly saline waters.

Within a prioritization scheme, however, to advance a diversity of cultivation or controlled plant production options using halophytes, which must operate in clear consideration of ecosystem and biodiversity services, and preferably within a demand-driven market structure, seems a logical avenue to advance the implementation of halophytes as crops and the appertaining knowledge to be derived from it.

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