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Article

Potential of Brackish Groundwater for Different Biosaline Agriculture Systems in the Brazilian Semi-Arid Region

Carla Ingryd Nojosa Lessa [1], Claudivan Feitosa de Lacerda [1,*], Cláudio Cesar de Aguiar Cajazeiras [2], Antonia Leila Rocha Neves [1], Fernando Bezerra Lopes [1], Alexsandro Oliveira da Silva [1], Henderson Castelo Sousa [1], Hans Raj Gheyi [3], Rafaela da Silva Nogueira [4], Silvio Carlos Ribeiro Vieira Lima [5], Raimundo Nonato Távora Costa [1] and Geocleber Gomes de Sousa [4]

1 Agricultural Engineering Department, Federal University of Ceará, Fortaleza 60455-760, Brazil
2 Geological Survey of Brazil-CPRM, Fortaleza 60135-101, Brazil
3 Academic Unit of Agricultural Engineering, Federal University of Campina Grande, Campina Grande 58840-000, Brazil
4 Institute of Rural Development, University of International Integration of Afro-Brazilian Lusofonia, Redenção 62790-000, Brazil
5 Secretariat of Economic Development and Labor of the State of Ceará, Fortaleza 60160-230, Brazil
* Correspondence: cfeitosa@ufc.br

Abstract: The objective of this research was to define the potential of brackish groundwater for 15 systems of biosaline agriculture in a representative area of the Brazilian semi-arid region. The study was conducted using a database of the State of Ceará, with 6284 wells having brackish water (EC $\geq$ 0.8 dS m^{-1} and discharge rate $\geq$ 0.5 m^3 h^{-1}). Our results show that the potential of brackish groundwater resources depends on the set of data: (i) production system (crop salt tolerance and water demand) and (ii) water source (salinity and well discharge rate). The joint analysis of these data shows that plant production systems with lesser water requirements, even with moderate tolerance levels to salt stress, present better results than more tolerant species, including halophytes and coconut orchards. About 41, 43, 58, 69, and 82% of wells have enough discharge rates to irrigate forage cactus (1.0 ha), sorghum (1.0 ha with supplemental irrigation), hydroponic cultivation, cashew seedlings, and coconut seedlings, respectively, without restrictions in terms of salinity. Otherwise, 65.8 and 71.2% of wells do not have enough water yield to irrigate an area of 1.0 ha with halophytes and coconut palm trees, respectively, butmore than 98.3 and 90.7% do not reach the water salinity threshold for these crops. Our study also indicates the need for diversification and use of multiple systems on farms (intercropping, association of fish/shrimp with plants), to reach the sustainability of biosaline agriculture in tropical drylands, especially for family farming.

Keywords: drylands; aquifers; salinity; biosalinity; sustainability

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1. Introduction

The semi-arid regions of the world suffer from water shortage and are increasingly vulnerable to extreme events, imposed by climate variability and enhanced by climate change on a global scale [1,2]. In particular, the tropical semi-arid regions are faced with several constraints that compromise sustainability [3–5] and the expansion of the agricultural sectors, such as high temperature, water shortage, poorly developed soils, and high salinity of groundwater sources [6–8]. Prolonged droughts, as observed in the Brazilian semi-arid region between 2012 and 2016 [9,10], cause severe losses in agricultural and livestock production, as well as impact other sectors of the economy [11].

Irrigated agriculture is responsible for the highest consumption of available water in arid and semi-arid regions [12,13]. However, farmers in these regions suffer from problems related to the availability and quality of water for agricultural production [14]. According to [15], most surface reservoirs present in the Brazilian semi-arid region have a capacity ranging from 1 to 1000 hm^3, with small (less than 10 hm^3) and medium (10 to 50 hm^3) sizes prevailing. Given the high evaporation rate and the scarcity of surface water in this region, the use of groundwater is a viable alternative [16].

According to data from the National Water Agency (ANA), in 2017 there were about 1.2 million wells drilled in the aquifers of Brazil [17]. In the Brazilian semi-arid region, there are about 160,000 wells [18], and a significant part of these water sources have a high salt concentration, with electrical conductivity of most water sources between 1.0 and 6.0 dS m^{-1} and an average discharge rate less than 3.0 m^3 h^{-1} [6,19–21]. According to [6], the largest proportion of these wells with brackish water is found in the fractured crystalline aquifers, followed by alluvial and sedimentary areas.

With the scarcity of low-salinity water for use in irrigated agriculture, the use of brackish water appears to be an alternative [21,22]. Although these brackish sources can meet the water needs of certain production systems, the high salt concentration is a constraint for the growth and productivity of most crops [23–25]. Plants under salt stress may present changes in their metabolic and biochemical activities due to the osmotic and ionic effects of excess salts in the root zone, with direct impacts on stomatal conductance and photosynthetic rate, inhibition of protein synthesis and enzymatic activities, and increased degradation of chlorophyll [26,27].

To partially circumvent salinity problems in agriculture, there is a vast literature on crop salt tolerance [28], as well as management strategies to reduce the impacts of excess salts on crop development [20]. In addition, there is a lot of information on the water needs of annual and perennial crops, and studies on the water potential of aquifers, which allow the elaboration of well-sized projects with water sustainability. However, the potential of these brackish water sources has only been assessed based on qualitative (water salinity) or quantitative (water yield) assessment [6,21,29]. According to quality indices, for example, a high percentage of the brackish groundwater (51%) in the Brazilian semi-arid region has been classified as poor quality for plant cultivation, while 87% integrated the best quality classes (excellent and good) for animal production [21]. Otherwise, studies that simultaneously evaluate the quantitative and qualitative potential of brackish groundwater for agricultural purposes have not been carried out to date. Therefore, this innovative approach needs to be developed to ensure the expansion of sustainable biosaline production under arid and semi-arid climates. The results of this type of research can give a more realistic guide for the use of brackish groundwater by farmers as well as for the improvement of public policies related to the agriculture sector.

Considering this new approach, our study tested the hypothesis that the potential of wells with brackish water in the Brazilian semi-arid region depends on the water salinity level, water discharge rates, and inherent characteristics of biosaline production systems (salt tolerance and water demand). Thus, the objective of this study was to define, based on qualitative and quantitative indicators, the potential of wells with brackish water for 15 agricultural production systems in a representative area of the Brazilian semi-arid region.

2. Material and Methods

2.1. Characterization of the Study Area

The Brazilian semi-arid region covers areas of nine States in the Northeast Region and one in the Southeast Region, covering 1262 municipalities. It has a total area of approximately 1.12 million km^2, and about 27 million inhabitants [30]. This study was carried out using a database from the State of Ceará (Figure 1). The State is made up of 184 municipalities, with a total area of 148,886 km^2, and a population of 8.9 million inhabitants. According to the Köppen classification, the State of Ceará has two types of climates: BSh (tropical semi-arid climate) and Aw (tropical climate with dry winter). However, the semi-arid tropical climate is predominant [31] in approximately 95% of the area of the state, with an average annual temperature of 27 °C, potential evapotranspiration of 1700 mm, and average annual rainfall from 500 to 800 mm, with around 80% concentrated during February to May [32].

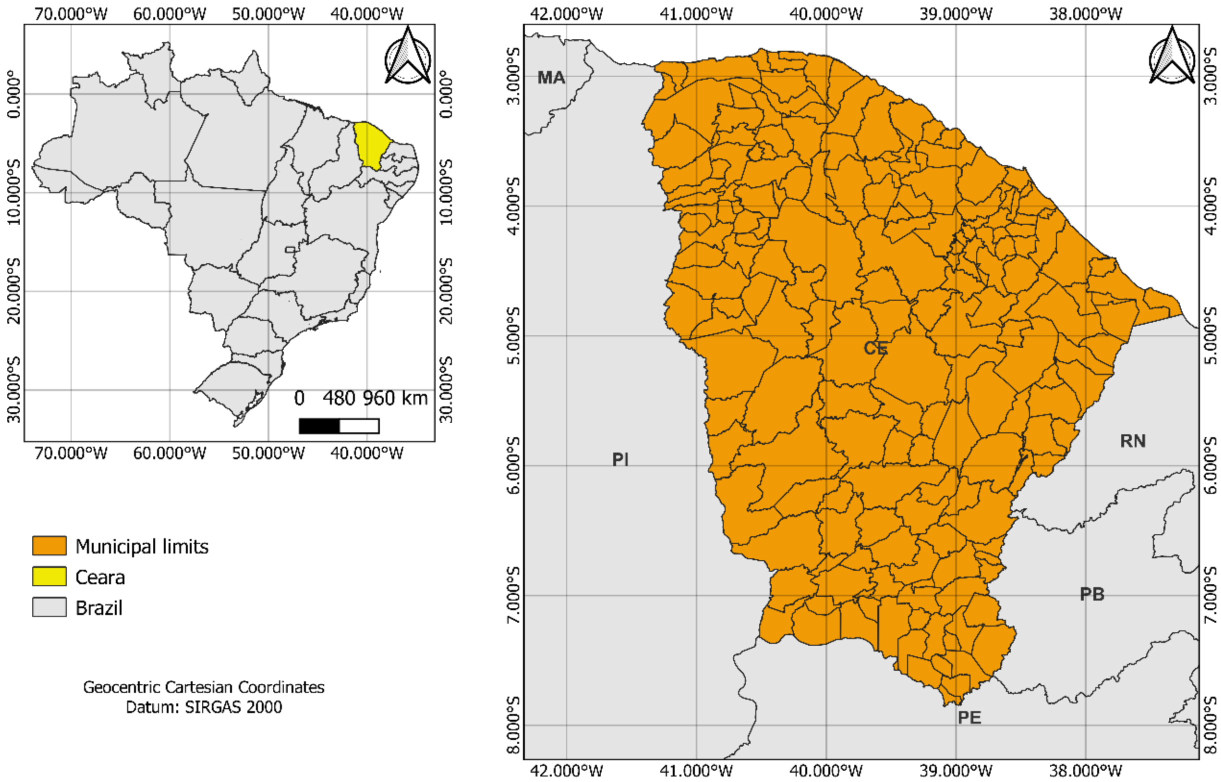

Figure 1. Geographic location of the study area. The acronyms indicate the states of the Northeast Region of Brazil that border the State of Ceará—CE: MA = Maranhão; PI = Piauí; RN = Rio Grande do Norte; PB = Paraiba; PE = Pernambuco.

2.2. Database Characterization

The research was carried out using a database of chemical analyses of water from wells in 179 municipalities in the State of Ceará, provided by the Superintendência de Obras Hidráulicas do Ceará (SOHIDRA) and by the Serviço Geológico do Brasil (CPRM). The selection of wells with brackish water was based on the electrical conductivity of the water (EC) $\geq$ 0.8 dS m^{-1} (quality criterion) and discharge rate (Q) $\geq$ 0.5 m^3 h^{-1} (water availability criterion).

The database consists of wells drilled from 1987 to 2021, totaling 25,497 wells, with 6284 wells (about 25% of the total) meeting the quality and water availability criteria established for the study (EC $\geq$ 0.8 dS m^{-1} and Q $\geq$ 0.5 m^3 h^{-1}). The database also includes relevant information, such as: city, geographic coordinates, drilling year, and depth. Table 1 presents the minimum, average, maximum, and median for electrical conductivity, total dissolved solids, discharge rate, and depth.

Table 1. Minimum, average, maximum, and median values for electrical conductivity of water (EC), total dissolved solids (TDS), discharge rate, and depth of the 6284 wells with brackish water from the Ceará State database.

Parameters	Minimum	Average	Maximum	Median
EC (dS m^{-1})	0.80	2.89	29.40	1.97
TDS (mg L^{-1})	508.8	1980.6	23,520	1260.8
Discharge (m^3 h^{-1})	0.50	4.10	180	2.48
Depth (m)	11.5	69.38	233	70

2.3. Selected Production Systems

To assess the potential use of brackish water, plant production systems and two fish and plant associations were considered, characterized as follows: (i) full irrigation (halophytes and maize); (ii) supplemental irrigation of annual crops (maize, sorghum, and cotton); (iii) irrigation of perennial crops (forage cactus, cashew, and coconut trees); (iv) hydroponics (vegetables); (v) production of seedlings in nurseries (coconut, cashew, and tree species from the Caatinga biome); (vi) ornamental plants; and (vii) association of fish and plants: (Tilapia—*Oreochromis niloticus plus* glycophytes and Tilapia *plus* halophytes). The selection of these production systems considered their adaptability to the semi-arid tropical climate, being commonly used in small and medium farms in the semi-arid region of Brazil.

2.4. Definition of Salinity Thresholds

The water salinity threshold for the 15 production systems was defined based on results published in the scientific literature (Table 2), considering a production loss of up to 10% (EC_{90}).

Table 2. Water salinity threshold for 15 production systems, assuming a maximum production loss of up to 10% (EC_{90}).

Production systems	EC_{90} (dS m^{-1}) *	References
1. Full irrigation of halophytes (Atriplex, Sarcorcórnia, etc.)	11.4	[33,34]
2. Full irrigation of maize	1.7	[28,35]
3. Supplemental irrigation of maize	3.2	[35–37]
4. Supplemental irrigation of cotton	5.1	[28,38,39]
5. Supplemental irrigation of sorghum	5.0	[28,40,41]
6. Irrigation of forage cactus	3.0	[42–45]
7. Irrigation of cashew orchards in sandy soils	5.0	[46–48]
8. Irrigation of coconut orchards in sandy soils	6.0	[49–51]
9. Hydroponics cultivation of vegetables	3.0	[52–55]
10. Coconut seedlings	4.5	[56,57]
11. Cashew seedlings	3.0	[58–60]
12. Seedlings of tree species native to Caatinga biome	2.5	[61]
13. Herbaceous ornamental plants	2.5	[62–64]
14. Tilapia *plus* glycophytes	3.0	**
15. Tilapia *plus* halophytes	9.0	***

* Electrical conductivity measured at 25 °C; ** Threshold for the glycophyte systems that will be used in association with fish (supplemental irrigation, hydroponics, forage cactus, and seedling production in nurseries); *** Threshold value for tilapia cultivation, according to [65–67].

In general, less restrictive water salinity thresholds were chosen, considering the existence of poorly developed soils in areas with a high occurrence of brackish groundwater in the Brazilian semi-arid region. A minimum leaching fraction of 15% is recommended to avoid excessive salt build-up, especially when full irrigation is used. The sodium adsorption ratio (SAR) should be previously evaluated in the case of soils with medium texture or with high clay content, although SAR values are not high in most water sources in the region studied [6]. In some cases, the potential for incrustation or corrosion must also be evaluated to avoid clogging problems in the irrigation system, especially in waters with a high concentration of carbonates and sulphate [28].

For supplemental irrigation of annual crops, the salinity thresholds are higher than for full irrigation, because of the possibility of leaching of part of the salts by rainwater [68]. However, for supplemental irrigation of cotton, it is recommended to use the threshold salinity value indicated for full irrigation, given the types of soils in which cotton is cultivated, which normally have high clay content. For perennial crops, both possibilities of full and supplemental irrigation were considered. Full irrigation of perennial crops such as coconut and cashew nut should be carried out in deep sandy soils and orchards in production. The implantation of new orchards must be performed at the beginning of the rainy season, with the use of supplemental irrigation with brackish water, if necessary.

For most cases, localized irrigation is recommended, as this method reduces the direct impact of salinity on the leaves. However, sprinkler irrigation may be used for annual crops, especially for supplemental irrigation of foragewith water of moderate salinity. Supplemental irrigation can be practiced during the rainy season in the Brazilian semi-arid region. Forage cactus should only be irrigated in the dry season.

The fish *plus* glycophytes system combines tilapia cultivation with plant production systems (supplemental irrigation of annual crops or forage cactus irrigation or seedling production in nurseries or hydroponic cultivation), and the average salinity threshold for plant cultivation was considered. For the fish *plus* halophyte system, the threshold value for tilapia cultivation (9.0 dS m^{-1}) was considered [65–67].

2.5. Definition of the Minimum Required Discharge Rates

The minimum discharge rate (Table 3) was defined according to the size of the enterprise, the water demand of each production system, and the time of functioning of the deep well (6 h per day).

Table 3. Minimum discharge rates (Q) required of wells for each production system *.

Production Systems/Enterprise Size	Required Water Discharge Rate (m^3 h^{-1})
Full irrigation of halophytes (Atriplex, Sarcorcórnia)—0.5 ha	2.0
Full irrigation of halophytes (Atriplex, Sarcorcórnia)—1.0 ha	4.0
Full irrigation of maize—0.5 ha	2.5
Full irrigation of maize—1.0 ha	5.0
Supplemental irrigation of annual crops (maize, cotton, sorghum)—0.5 ha	1.25
Supplemental irrigation of annual crops (maize, cotton, sorghum)—1.0 ha	2.50
Irrigation of forage cactus—0.5 ha	1.0
Irrigation of forage cactus—1.0 ha	2.0
Irrigation of cashew orchards in sandy soils—0.5 ha	1.6
Irrigation of cashew orchards in sandy soils—1.0 ha	3.2
Irrigation of coconut orchards in sandy soils—0.5 ha	3.0
Irrigation of coconut orchards in sandy soils—1.0 ha	6.0
Hydroponic cultivation of vegetables (100 m^2)	1.0
Cashew seedlings in nurseries (2000 seedlings)	0.5
Coconut seedlings in nurseries (2000 seedlings)	0.5
Seedlings of tree species native to Caatinga biome (2000 seedlings)	0.5
Herbaceous ornamental plants (2000 plants)	0.5
Tilapia *plus* glycophytes	1.5
Tilapia *plus* halophytes	2.5

For full irrigation of maize, a daily water depth of 5.0 mm was considered [69], with localized irrigation and a wetted area equal to 50% of the total area. This value represents the water consumption at the stage of maximum crop demand, with lower consumption at the other stages. For longer irrigation intervals, a 50–100 m^3 cistern/tank will be required to store water from the well on days without an irrigation event. For supplemental irrigation of annual crops, the adequate discharge rate will be half of that required for full irrigation [69–71], with the possibility of storing rainwater or well water during the dry spells.

For forage cactus irrigation, 40,000 plants ha^{-1} and an irrigation depth of 1.0 mm per day were considered [72,73], with weekly irrigation during the dry season, which requires the storage of well water. For the dwarf cashew, 204 plants ha^{-1} were considered with an average water application of 80 L $plant^{-1}$ day^{-1} [74]. For dwarf green coconut, 200 plants ha^{-1} were considered with an average water application rate of 150 L $plant^{-1}$ day^{-1} [75,76].

For the fish *plus* glycophytes system, the discharge rate required for 0.4 ha of supplemental irrigation of annual crops, or 0.5 ha of forage cactus was considered, which is also sufficient for hydroponics or seedling production. For the fish *plus* halophytes system, the discharge rate required for 0.5 ha of halophytes was considered. The total water required by each system also includes evaporation losses in fish farming. A total volume of 100 m^3 was considered for the cultivation of fish, which can be stored in one or more tanks.

2.6. Criteria for Defining the Potential of the Wells

The criteria for water quality (threshold salinity, Table 2) and water availability (water discharge required, Table 3) were adopted, and their respective adequacy and non-adequacy values, as described in Table 4:

Table 4. Water quality criteria and well productivity.

Electrical Conductivity (EC_{90})	Discharge (Q)	Symbol
Adequate (ad)	Adequate (ad)	EC_{ad} and Q_{ad}
Inadequate (nad)	Adequate (ad)	EC_{nad} and Q_{ad}
Adequate (ad)	Inadequate (nad)	EC_{ad} and Q_{nad}
Inadequate (nad)	Inadequate (nad)	EC_{nad} and Q_{nad}

For the irrigation of halophytes, annual crops, and perennial crops, the irrigable area in hectares was estimated. For this calculation, the following data were considered: The volume of water produced by the well without salinity restriction (m^3) and the volume required for each cultivation system (m^3 ha^{-1}). The daily water volume produced by the well was obtained by multiplying the discharge rate by 6 (time of functioning).

2.7. Data Analysis

Data of electrical conductivity and discharge rate of the wells were organized in spreadsheets in the computer program Microsoft Excel in a file containing the respective geographic coordinates to facilitate the manipulation of the data. Then, georeferenced maps were made for each biosaline production system, using the Quantum GIS 3.22 program [77].

3. Results

3.1. Irrigation of Halophytes

Data analysis showed that 3637 wells (57.9%) have adequate electrical conductivity and discharge for full irrigation of halophytes for an area of 0.5 ha (Figure 2A). However, 70 wells (1.1%) do not have adequate electrical conductivity, but their discharge rate is adequate, 2539 wells (40.4%) have adequate electrical conductivity, but the water availability is insufficient, and 38 wells (0.6%) do not have an adequate discharge rate and the electrical conductivity is higher than the salinity threshold. For an area of 1.0 ha (Figure 2B), 2113 wells (33.7%) are adequate both from the point of view of electrical conductivity and water availability, 29 wells (0.5%) only have adequate discharge rates, 4063 wells (64.6%) only have adequate electrical conductivity, and 79 wells (1.2%) do not have suitable salinity or water availability.

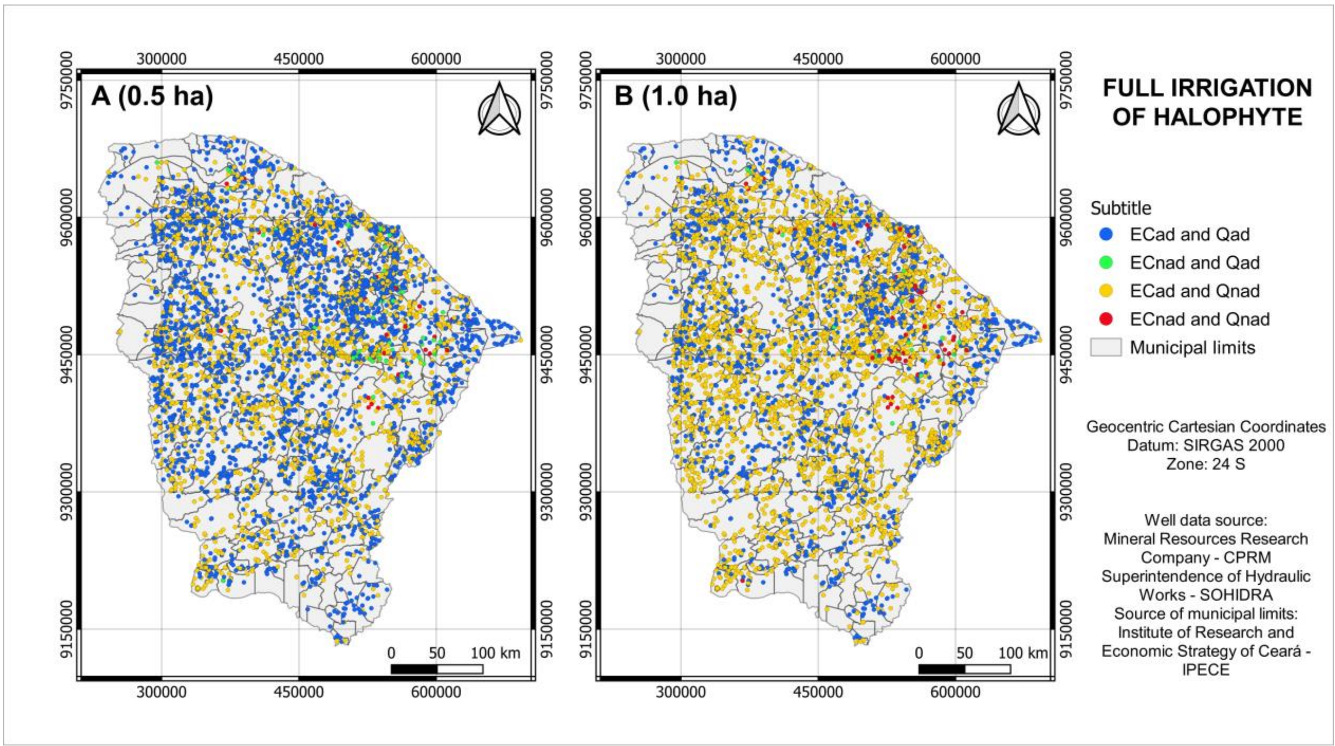

Figure 2. Potential of brackish groundwater in the State of Ceará (Northeast Brazil) for full irrigation of halophytes in 0.5 ha (**A**) and 1.0 ha (**B**), based on the threshold electrical conductivity of the irrigation water (EC) and discharge rate (Q). EC_{ad}: adequate electrical conductivity; EC_{nad}: inadequate electrical conductivity; Q_{ad}: adequate discharge; Q_{nad}: inadequate discharge.

3.2. Full and Supplemental Irrigation of Annual Crops

For full irrigation of maize, with an area of 0.5 ha (Figure 3A), about 1410 wells (22.4%) show EC and Q suitability, 1729 wells (27.5%) show inadequate EC and adequate Q, 1263 wells (20.1%) have adequate EC and inadequate Q, and 1882 wells (30.0%) do not have adequate EC or adequate Q. For 1.0 ha (Figure 3B), only 794 wells (12.6%) have adequate EC and Q, 839 wells (13.3%) only have adequate Q, 1879 wells (30.0%) only have adequate EC, and 2772 wells (44.1%) have salinity above the threshold and do not reach the minimum discharge required for the crop.

For supplemental irrigation of maize, for 0.5 ha (Figure 3C), 3278 wells (52.2%) meet the water demand of the crop and have an EC within the salinity threshold of the crop. However, 1248 wells (19.8%) only have adequate Q, 1211 wells (19.3%) only have adequate electrical conductivity of water, and 547 wells (8.7%) did not present either adequate electrical conductivity or water availability. For the area of 1.0 ha (Figure 3D), 2314 wells (36.8%) fit according to EC and Q, 825 wells (13.1%) only have adequate discharge, 2175 wells (34.6%) only have adequate electrical conductivity, and 970 wells (15.5%) are not suitable due to the high salinity and low discharge rate.

Of the 6284 wells evaluated for supplemental irrigation of sorghum in an area of 0.5 ha (Figure 4A), 62.0% (3898 wells) have adequate EC and Q, 10.0% (628 wells) only have adequate Q, 23.3% (1462 wells) have adequate EC and inadequate Q, and 4.7% (296 wells) do not have adequate EC and Q. For an area of 1.0 ha (Figure 4B), 43.5% (2732 wells) of the wells have adequate EC and Q, 6.5% (407 wells) have inadequate EC and adequate Q, 41.8% (2628 wells) have adequate EC and inadequate Q, and 8.2% (517 wells) do not have adequate EC or Q.

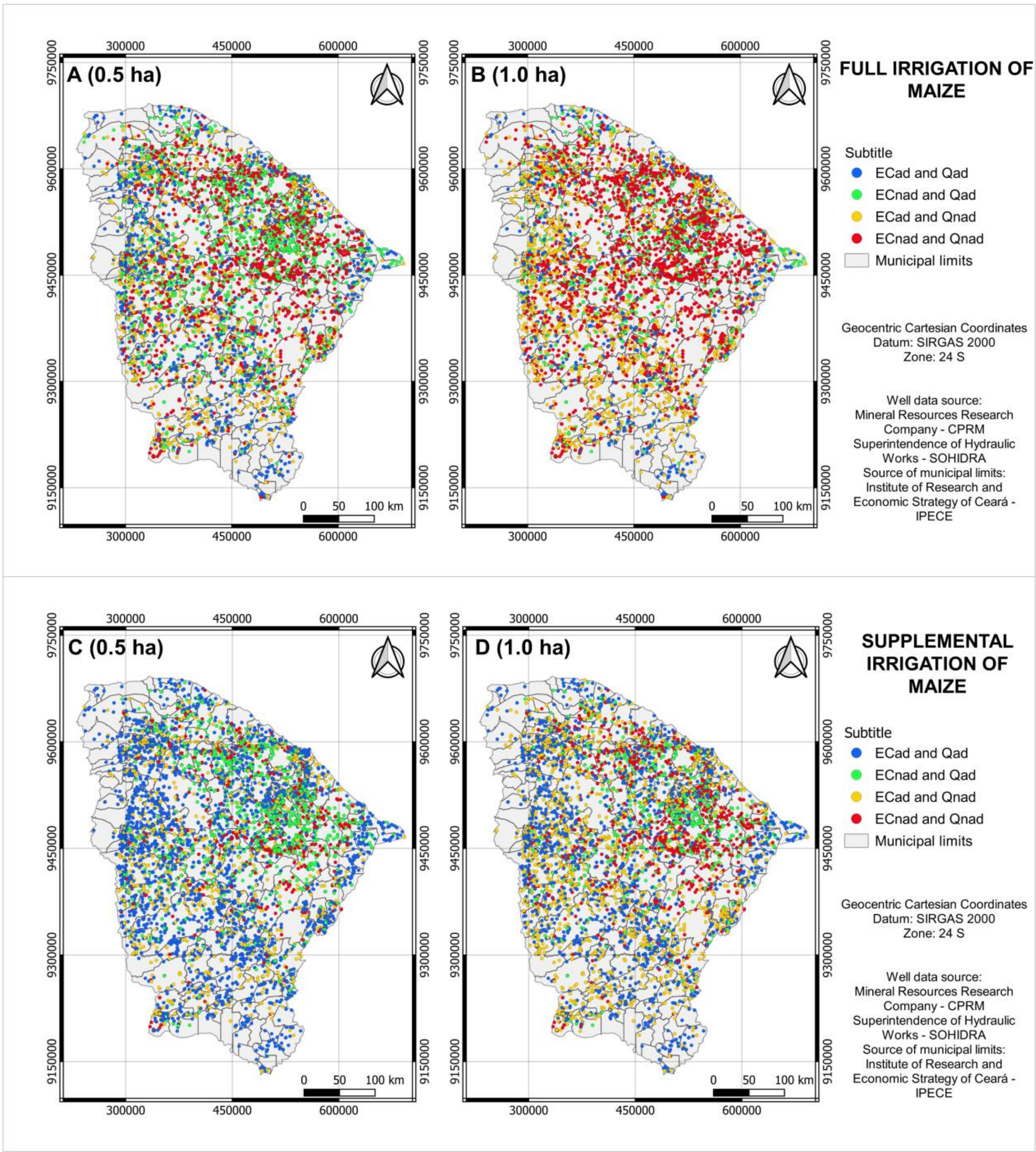

Figure 3. Potential of brackish groundwater in the State of Ceará (Northeast Brazil) for full irrigation of maize in 0.5 ha (**A**) and 1.0 ha (**B**), and supplemental irrigation of maize in 0.5 ha (**C**) and 1.0 ha (**D**), based on the threshold electrical conductivity of the irrigation water (EC) and discharge rate (Q). EC_{ad}: adequate electrical conductivity; EC_{nad}: inadequate electrical conductivity; Q_{ad}: adequate discharge; Q_{nad}: inadequate discharge.

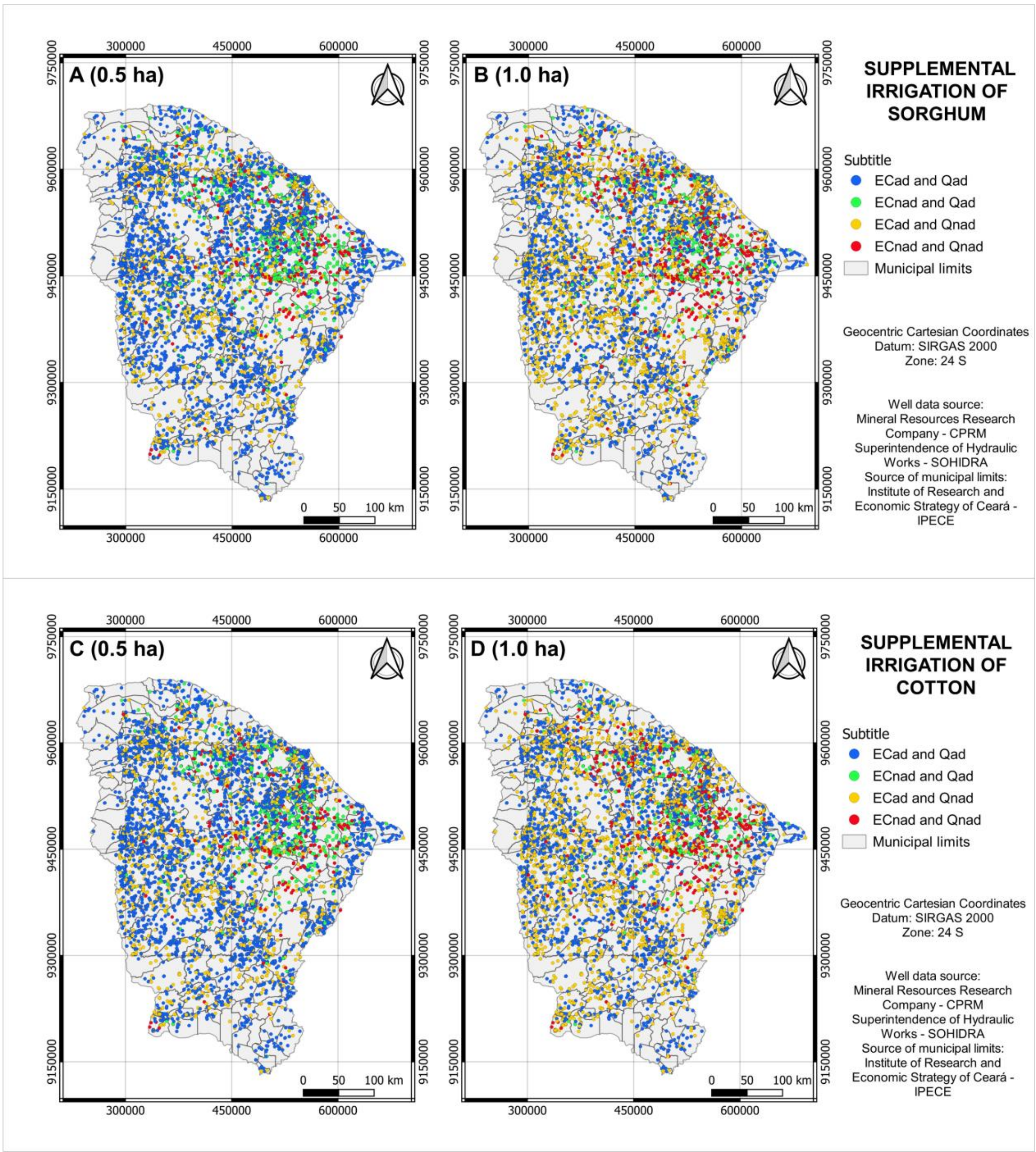

Figure 4. Potential of brackish groundwater in the State of Ceará (Northeast Brazil) for supplemental irrigation of sorghum in 0.5 ha (**A**) and 1.0 ha (**B**), and supplementary irrigation of cotton in 0.5 ha (**C**) and 1.0 ha (**D**), based on the threshold electrical conductivity of the irrigation water (EC) and discharge rate (Q). EC_{ad}: adequate electrical conductivity; EC_{nad}: inadequate electrical conductivity; Q_{ad}: adequate discharge; Q_{nad}: inadequate discharge.

For the practice of supplemental irrigation of cotton in an area of 0.5 ha (Figure 4C), 62.6% of wells (3938 wells) achieve adequacy in terms of salinity and water availability, 9.3% (588 wells) only have adequate Q, 23.5% (1477 wells) only have adequate EC, and 4.5% (281 wells) do not have either adequate water electrical conductivity or well discharge. Considering an area of 1.0 ha (Figure 4D), 44.0% of wells (2760 wells) have adequate water electrical conductivity and discharge, 6.0% (379 wells) only have adequate Q, 42.2% (2655 wells) only have adequate EC, and 7.8% (490 wells) are limited by both high salinity and low water availability.

3.3. Irrigation of Perennial Crops

In the irrigation of forage cactus for an area of 0.5 ha (Figure 5A), 3624 wells (57.7%) are adequate in terms of salinity and water availability, 1603 wells (25.5%) only have adequate Q, 703 wells (11.2%) only have adequate EC, and 354 wells (5.6%) have inadequate EC and Q. For an area of 1.0 ha (Figure 5B), 2594 wells (41.3%) present adequate EC and Q, 1108 wells (17.6%) only have adequate Q, 1733 wells (27.6%) only have adequate EC, and 849 wells (13.5%) do not have adequate EC or Q.

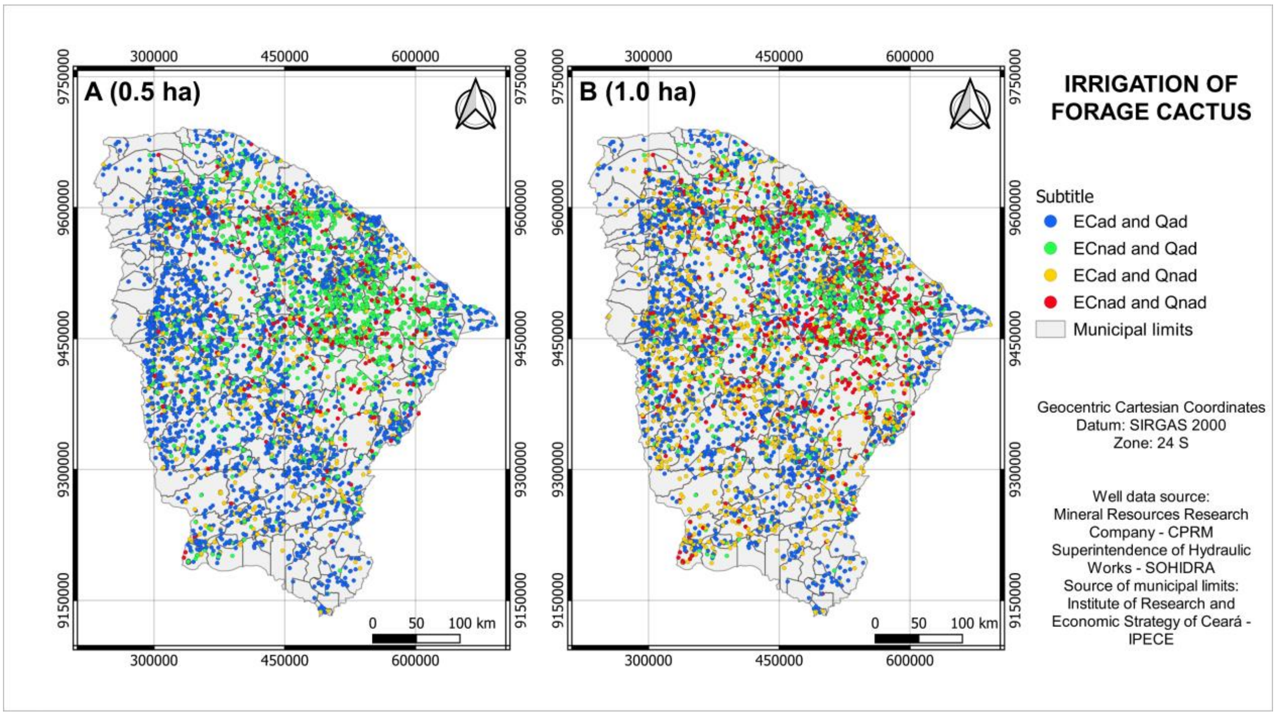

Figure 5. Potential of brackish groundwater in the State of Ceará (Northeast Brazil) for full irrigation of forage cactus in 0.5 ha (**A**) and 1.0 ha (**B**), based on the threshold electrical conductivity of the irrigation water (EC) and discharge rate (Q). EC_{ad}: adequate electrical conductivity; EC_{nad}: inadequate electrical conductivity; Q_{ad}: adequate discharge; Q_{nad}: inadequate discharge.

For the management of coconut irrigation in an area of 0.5 ha (Figure 6A), 41.2% of wells (2592 wells) have adequate electrical conductivity and discharge, 3.5% (217 wells) only have adequate Q, 49.4% (3105 wells) are limited only by low discharge, and 5.9% (370 wells) have problems of high salinity and low water availability. For an area of 1.0 ha, 19.5% (1225 wells) have adequate EC and Q, 1.4% (88 wells) have adequate Q only, 7.9% (499 wells) do not have adequate water electrical conductivity or discharge, and 71.2% (4472 wells) are limited by low water availability.

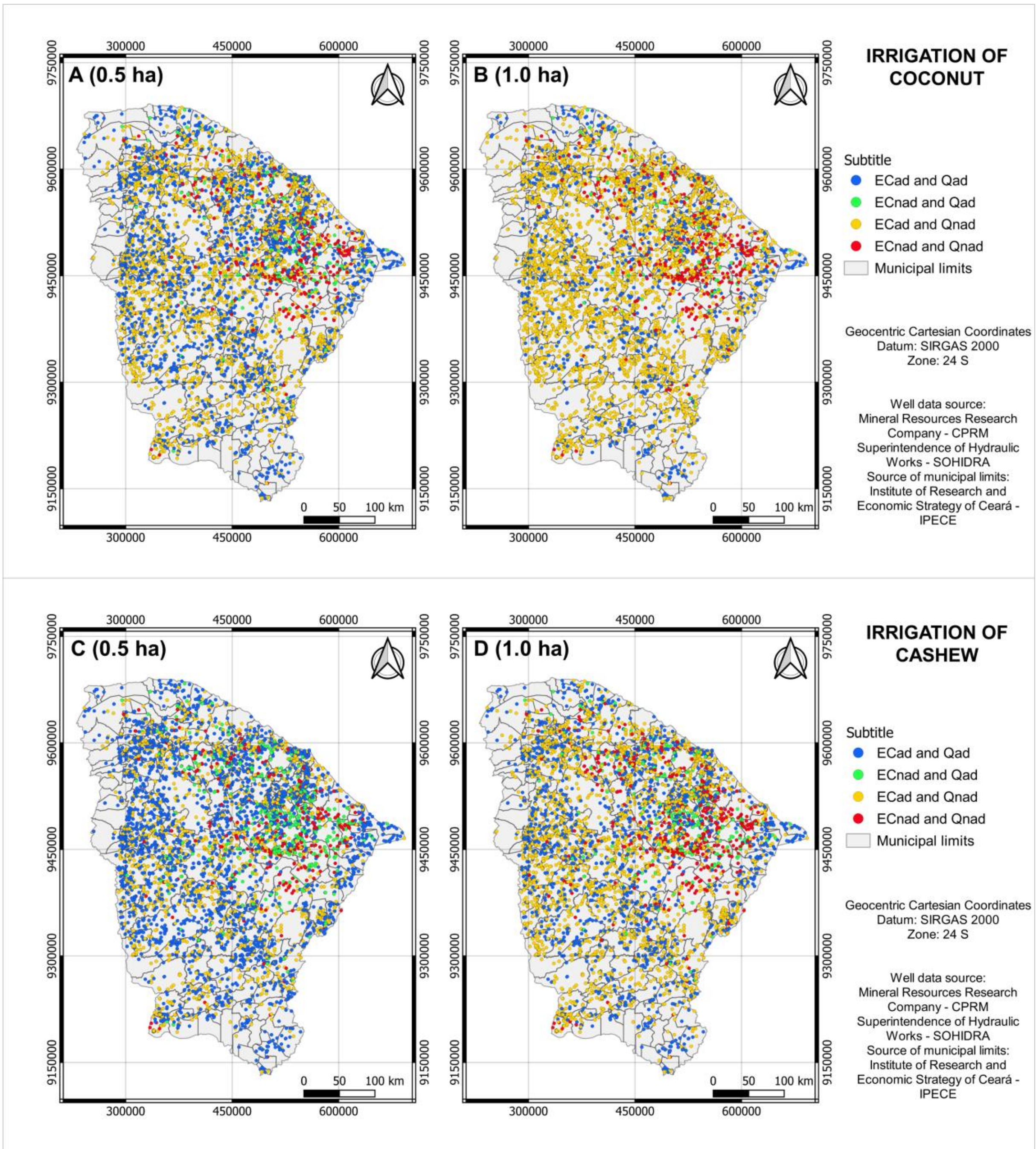

Figure 6. Potential of brackish groundwater in the State of Ceará (Northeast Brazil) for coconut irrigation in 0.5 ha (**A**) and 1.0 ha (**B**), and cashew irrigation in 0.5 ha (**C**) and 1.0 ha (**D**), based on the threshold electrical conductivity of the irrigation water (EC) and discharge rate (Q). EC_{ad}: adequate electrical conductivity; EC_{nad}: inadequate electrical conductivity; Q_{ad}: adequate discharge; Q_{nad}: inadequate discharge.

For irrigation of cashew in an area of 0.5 ha, it is observed that 55.7% (3501) of the wells have adequate EC and Q, 8.8% (554 wells) only have adequate Q, 29.6% (1859 wells) only have adequate EC, and 5.9% (370 wells) do not have adequate EC and Q (Figure 6C). For an area of 1.0 ha, 35.1% (2208) of the wells have adequate EC and Q, 5.0% (316 wells) do not have adequate EC, but have adequate Q, 9.7% (608 wells) do not have adequate EC or Q, while 50.2% (3152 wells) are unproductive due to low water availability (Figure 6D).

3.4. Seedlings, Hydroponics and Multiple Systems

Figure 7 highlights seedling production systems in nurseries and hydroponic cultivation. To produce 2000 coconut seedlings, 5195 wells (82.7%) achieve adequacy in terms of threshold water salinity and well discharge, while 1089 (17.3%) are limited by high salinity. To produce 2000 cashew seedlings (Figure 7B), 4327 wells (68.8%) have adequate water electrical conductivity and discharge, and 1957 (31.2%) are limited by high salinity. As for the production of 2000 seedlings of trees from the Caatinga biome or ornamental plants (Figure 7C), 3853 wells (61.3%) have adequate electrical conductivity and discharge, and 2431 wells (38.7%) have electrical conductivity above the water salinity threshold. For the hydroponic cultivation of vegetables in an area of 100 m^2 (Figure 7D), 3624 wells (57.7%) have adequate water electrical conductivity and discharge, 1603 wells (25.5%) only have adequate Q, 703 wells (11.2%) only have adequate EC, and 354 (5.6%) are limited by both high salinity and low water availability.

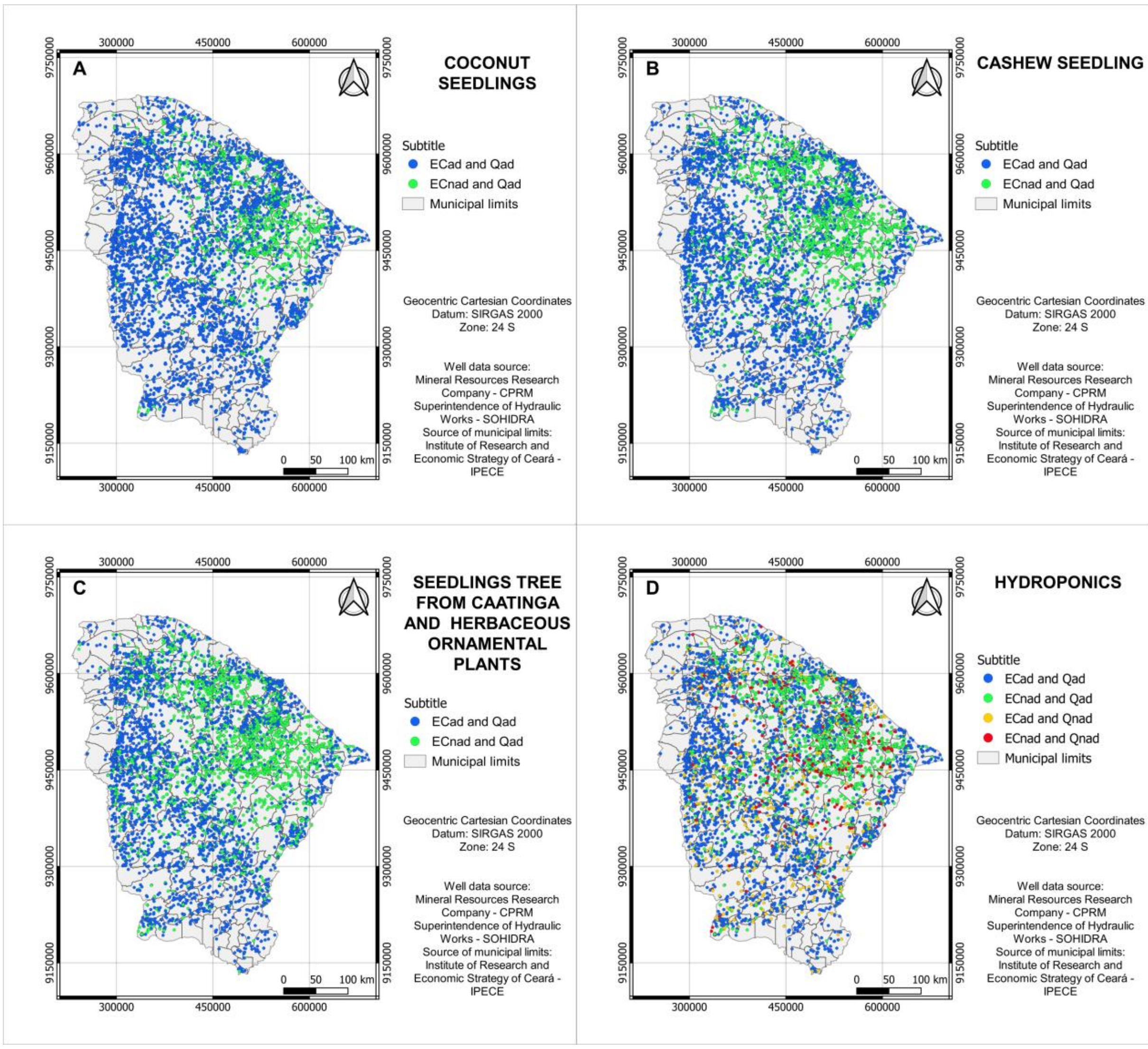

Figure 7. Potential of brackish groundwater in the State of Ceará (Northeast Brazil) to produce 2000 seedlings in nurseries of coconut (**A**), cashew (**B**), and trees native to the Caatinga biome/ornamental plants (**C**)), and to produce vegetables in hydroponic cultivation of 100 m^2 (**D**), based on the threshold electrical conductivity of the irrigation water (EC) and discharge rate (Q). EC_{ad}: adequate electrical conductivity; EC_{nad}: inadequate electrical conductivity; Q_{ad}: adequate discharge; Q_{nad}: inadequate discharge.

For the association of tilapia *plus* glycophytes (0.4 ha of supplemental irrigation of annual crops, or 0.5 ha of forage cactus, or 100 m^2 hydroponic cultivation, or production of 2000 seedlings in nurseries), 2982 wells (47.5%) have adequate EC and Q, 1272 wells (20.2%) have adequate Q but the electrical conductivity is not adequate, 1345 wells (21.4%) only have adequate EC, and 685 wells (10.9%) do not have an adequate discharge rate or electrical conductivity (Figure 8A). For the association tilapia *plus* 0.5 ha of halophytes (Figure 8B) 3042 wells (48.4%) have EC and Q adequacy, 97 wells (1.5%) have inadequate EC and adequate Q, 3016 wells (48.0%) have adequate EC and inadequate Q, and 129 (2.1%) do not have adequate EC or adequate Q.

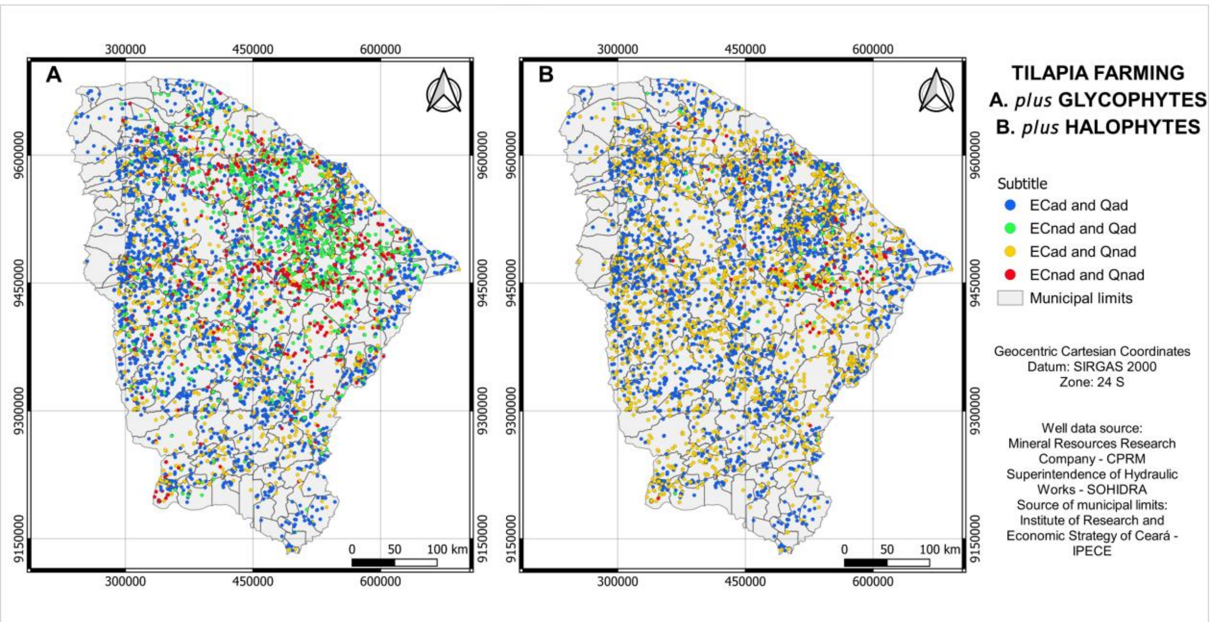

Figure 8. Potential of brackish groundwater in the State of Ceará (Northeast Brazil) for associations of fish (tilapia) *plus* glycophytes (**A**) and fish (tilapia) *plus* halophytes (**B**), based on the threshold electrical conductivity of the irrigation water (EC) and discharge rate (Q). EC_{ad}: adequate electrical conductivity; EC_{nad}: inadequate electrical conductivity; Q_{ad}: adequate discharge; Q_{nad}: inadequate discharge.

However, when only tilapia production was considered, the numbers were much more positive (Figure 9), since this production system in tanks requires less water and tilapia has a high tolerance to water salinity. For tilapia production in tanks with a total volume of up to 100 m^3, 5047 wells (80.3%) are adequate in terms of EC and Q, 180 wells (2.9%) only have adequate Q, 1011 wells (16.1%) only have adequate EC, and 46 wells (0.7%) do not have adequate conditions for both criteria (Figure 9).

Table 5 summarizes all the data on the number of wells with respective suitability categories for the different biosaline systems evaluated.

Table 5. Number and percentage of wells for the productive systems tested and considering the different suitability criteria.

Production Systems	EC_{ad} and Q_{ad^*}		EC_{nad} and Q_{ad}		EC_{ad} and Q_{nad}		EC_{nad} and Q_{nad}	
	Number of Wells	(%)	Number of Wells	(%)	Number of Wells	(%)	Number of Wells	(%)
Full irrigation of halophyte (0.5 ha)	3637	57.9	70	1.1	2539	40.4	38	0.6
Full irrigation of halophyte (1.0 ha)	2113	33.7	29	0.5	4063	64.6	79	1.2
Full irrigation of maize (0.5 ha)	1410	22.4	1729	27.5	1263	20.1	1882	30.0
Full irrigation of maize (1.0 ha)	794	12.6	839	13.3	1879	30.0	2772	44.1

Table 5. *Cont.*

Production Systems	EC_{ad} and Q_{ad}*		EC_{nad} and Q_{ad}		EC_{ad} and Q_{nad}		EC_{nad} and Q_{nad}	
	Number of Wells	(%)	Number of Wells	(%)	Number of Wells	(%)	Number of Wells	(%)
Supplemental irrigation of maize (0.5 ha)	3278	52.2	1248	19.8	1211	19.3	547	8.7
Supplemental irrigation of maize (1.0 ha)	2314	36.8	825	13.1	2175	34.6	970	15.5
Supplemental irrigation of sorghum (0.5 ha)	3898	62.0	628	10.0	1462	23.3	296	4.7
Supplemental irrigation of sorghum (1.0 ha)	2732	43.5	407	6.5	2628	41.8	517	8.2
Supplemental irrigation of cotton (0.5 ha)	3938	62.6	588	9.3	1477	23.5	281	4.5
Supplemental irrigation of cotton (1.0 ha)	2760	44.0	379	6.0	2655	42.2	490	7.8
Irrigation of forage cactus (0.5 ha)	3624	57.7	1603	25.5	703	11.2	354	5.6
Irrigation of forage cactus (1.0 ha)	2594	41.3	1108	17.6	1733	27.6	849	13.5
Irrigation of coconut (0.5 ha)	2592	41.2	217	3.5	3105	49.4	370	5.9
Irrigation of coconut (1.0 ha)	1225	19.5	88	1.4	499	7.9	4472	71.2
Irrigation of cashew (0.5 ha)	3501	55.7	554	8.8	1859	29.6	370	5.9
Irrigation of cashew (1.0 ha)	2208	35.1	316	5.0	608	9.7	3152	50.2
Coconut seedlings (2000 seedlings)	5195	82.7	1089	17.3	-	-	-	-
Cashew seedlings (2000 seedlings)	4327	68.8	1957	31.2	-	-	-	-
Caatinga Seedlings/ornamental (2000 seedlings)	3853	61.3	2431	38.7	-	-	-	-
Hydroponic cultivation (100 m^2)	3624	57.7	1603	25.5	703	11.2	354	5.6
Tilapia farming *plus* glycophytes	2982	47.5	1272	20.2	1345	21.4	685	10.9
Tilapia farming *plus* halophytes	3042	48,4	97	1.5	3016	48.0	129	2.1

* EC_{ad}: adequate electrical conductivity; EC_{nad}: inadequate electrical conductivity; Q_{ad}: adequate discharge; Q_{nad}: inadequate discharge.

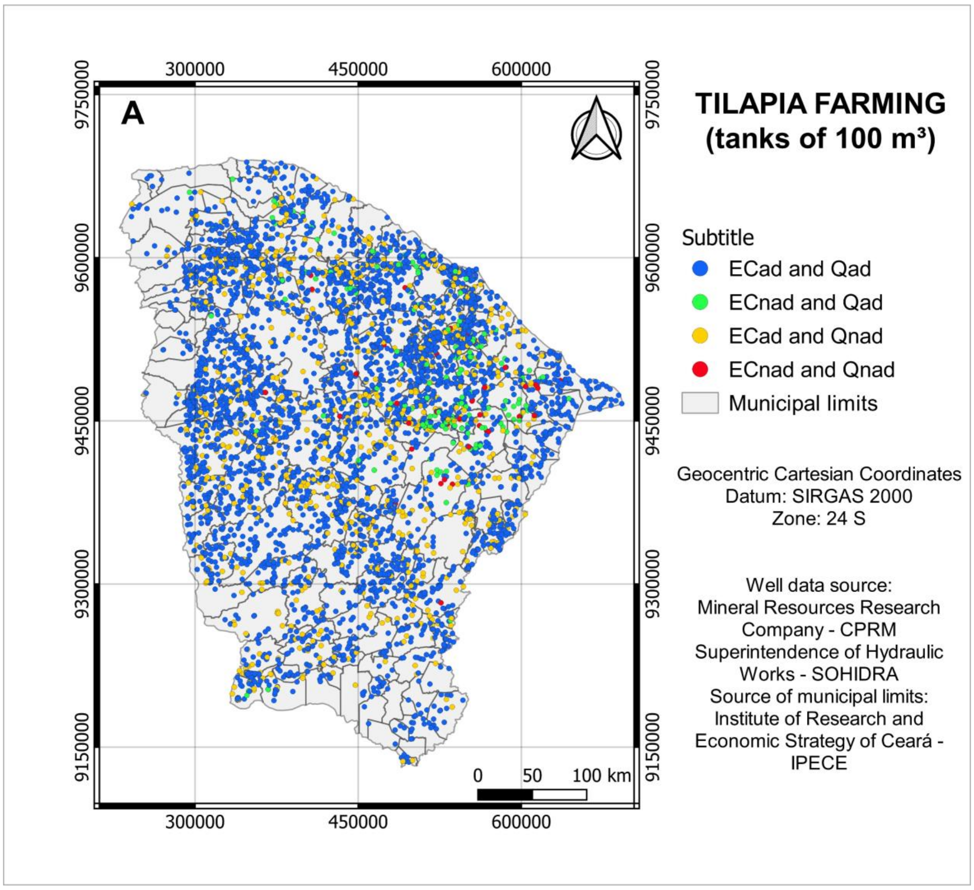

Figure 9. Potential of brackish groundwater in the State of Ceará (Northeast Brazil) for raising tilapia in tanks with a total volume of 100 m^3, based on the threshold electrical conductivity of the irrigation water (EC) and discharge rate (Q). EC_{ad}: adequate electrical conductivity; EC_{nad}: inadequate electrical conductivity; Q_{ad}: adequate discharge; Q_{nad}: inadequate discharge.

3.5. Estimated Irrigated Area for Cropping Systems

Considering the sampling of wells with brackish water (6284 wells distributed throughout the State of Ceará), the discharge required by each production system, and the water productivity of each well, it was possible to estimate the potential irrigable area for each system, without restrictions in terms of salinity (Table 6). Forage cactus has the largest potential irrigable area of the evaluated systems, followed by systems with supplemental irrigation (cotton, sorghum, and maize), almost all of which has more than 9000 ha. The smallest irrigable areas were found in the irrigation systems for coconut and full irrigation for maize.

Table 6. Potential of unrestricted irrigable area with brackish water from wells in the Brazilian semi-arid region.

Production Systems	Irrigable Area (ha)
1. Full irrigation of halophytes (Atriplex, Sarcorcórnia)	6426
2. Full irrigation of maize	2566
3. Supplemental irrigation of maize	7970
4. Supplemental irrigation of sorghum	9213
5. Supplemental irrigation of cotton	9287
6. Irrigation of forage cactus	9660
7. Irrigation of coconut in sandy soils	4026
8. Irrigation of cashew in sandy soils	7197

4. Discussion

In this study, we sought to define the potential of brackish groundwater sources in the State of Ceará, a representative area of the Brazilian semi-arid region, based on the water productivity of groundwater wells, the salinity level of the water, and the water demand/salt tolerance of 15 production systems. The analyses showed that low discharge rates of brackish groundwater wells predominate in the Brazilian semi-arid region, a factor that reduces water availability and restricts enterprises to family farmers. However, it is possible to identify more promising production systems, due to their high capacity to tolerate water salinity levels, lower water demand, or both. Therefore, the expansion of biosaline agriculture in the tropical semi-arid region is not defined only by the salt tolerance of the crop.

Halophytes constitute the plant system with the highest tolerance to salinity among those analyzed, and can be irrigated with high salinity water, notably in soils with good natural drainage [33,34]. Halophytes can withstand high levels of salinity, while almost 99% of other plant species (glycophytes) have some level of sensitivity to salts [78,79]. Halophytes also show good adaptability to arid and semi-arid regions and can be cultivated under rainfed farming or in saline soils, and act as alternative forage plants, such as *Atriplex* spp., *Salicornia* spp. and *Distichlis palmeri* [80–82]. However, our data showed that about 65% of the wells with brackish water do not have enough water volume to irrigate an area of 1.0 ha with halophyte plants, although more than 95% have no salinity restriction (Figure 2). For the coconut, a salinity-tolerant glycophyte [83], the low discharge limitation affects 71% of the wells due to the high-water demand of this palm species, even though more than 80% of the water sources do not reach the salinity threshold for the crop (Figure 6). These results demonstrate that tolerance of crops to salinity is important, but it is not the only option to cope with salinity problems in semi-arid regions [84,85].

Annual crops are also characterized by relatively high-water demand and varying degrees of salt tolerance [28,86,87]. Among the annual species studied, maize is the most salt-sensitive [28,36] and has the highest water requirement. For this crop, it was observed that only 13% of the wells are adequate for the cultivation of 1.0 ha under full irrigation, while 87% are limited by low discharge rate, high salinity, or both (Figure 3). However, when supplemental irrigation is used, the numbers are much more positive, reaching a level of adequacy of about 37%. For cotton and sorghum crops, levels of adequacy with the use of supplemental irrigation were even higher (Figure 4), given the high salt tolerance of these two crops [39,88], compared to maize. The beneficial effects of supplemental irrigation with brackish water have been demonstrated in the Brazilian semi-arid region, with high efficiency in productive and economic terms [37]. Supplemental irrigation also results in low accumulation of salts in the soil, and increases photosynthesis rates and water use efficiency, demonstrating that this practice reduces the water deficit without causing significant salt damage to the crop [68]. In the context of biosaline agriculture, supplemental irrigation can reduce the losses of rainfed agriculture, especially in periods of dry spells, and is a decisive tool to deal with the limitations of the water availability in semi-arid zones both currently and when considering the future risks associated with global climate change [89,90]. In our study, the systems with supplemental irrigation of maize with brackish water resulted in larger irrigable areas than for the cultivation of halophytes (Table 6).

Plant production systems with lower water requirements presented the best results (Figure 5), even with moderate tolerance to salt stress. The forage cactus, a species with CAM metabolism [91,92], contrasted with the coconut palm trees, presenting adequacy of salinity and water availability of 41%, while coconut reached only 19.5%. Therefore, for perennial crops, it is recommended that species with low water demand should be used. For forage cactus (*Opuntia fícus*, *Nopalea cochenillifera*, *Opuntia* sp., *Opuntia stricta*) the total annual irrigation does not exceed 200 mm, with a low salt load applied to the soil during the dry season. Forage cactus is an important energy source for animal feed, as it has a high content of carbohydrates, total digestible nutrients, and water [93–95], and can also be component of multiple systems involving the use of brackish water and fish or in systems intercropped with gliricidia and other plant species [44,96,97]. The use of mulch and other water and soil conservation techniques are also recommended for the cultivation of forage cactus and other species when irrigated with brackish water [20,98,99], considering the need to increase water use efficiency in the tropical semi-arid region [13].

The cultivation of forage cactus and supplemental irrigation of annual crops also stand out in terms of the potential irrigable area without salinity restrictions (Table 6), surpassing more salinity-tolerant crops such as halophytes and coconut palm trees, and with lower risks of soil degradation. For forage cactus, the total irrigable area would be more than 9000 ha, obtained from 6284 wells with brackish water, which represent about 25% of the total number of wells contained in the database (25,497 wells). If we consider the total of 160,000 wells in the Brazilian semi-arid region [20], the total number of wells with adequate brackish water would reach around 44,000, resulting in greater irrigable areas for forage cactus and other productive systems. However, the size of the enterprise is limited by the discharge rate of each well, and effort must be made towards having a diversification of biosaline agriculture systems in areas of family farming, which can produce food to boost local businesses and fodder to feed the animals on farms. It should be noted that 65% of rural establishments in the Northeast Region of Brazil have an area of less than 10 ha, and 79% of establishments are classified as family farming [100], which strengthens the need for diversification of production systems as a way of achieving social and economic sustainability of family production.

Plant systems in nurseries reach high levels of adequacy (Figure 7), including coconut seedlings (83%), cashew seedlings (69%), and tree species native to the Caatinga biome/ornamental plants (61%). This decreasing suitability is in accordance with the salt tolerance of the species in the initial growth stage, which decreases in the same order [62,101–103]. For the hydroponic production of leafy vegetables, the adequacy level reached about 58%; this system has aroused the interest of researchers and farmers in the Brazilian semi-arid region [104–106]. Hydroponics can also be included in solar energy production systems, using semi-transparent panels [107].

The production of tilapia in tanks presents a high degree of adaptability to salinity and requires little water, reaching a degree of adequacy greater than 80% (Figure 9). According to [21], the potential for using brackish water in the Brazilian semi-arid region is higher for pisciculture than for agriculture. Fish farming can also be done in combination with plant systems, such as halophytes, supplemental irrigation, seedling production, hydroponic cultivation, and forage cactus production, with a high degree of adequacy, as biosaline systems (Figure 8). These combined systems allow the multiple use of water, as well as the use of nutrients contained in wastewater from fish farming [108–111]. Obviously, the degree of adequacy decreases for the combined crop, as demonstrated by comparing Figure 8 (associations of tilapia with vegetables) and Figure 9 (only tilapia cultivation). These differences are explained by the limitation of salinity in glycophytes or by the greater water demand of plant systems. The shrimp *Litopenaeus vannamei* is also tolerant of high salinity [112] and its cultivation has grown in Brazilian inland areas [82]. The option exists for it to form associations with glycophytes and halophytes using brackish water, despite requiring greater investment and more technology than tilapia farming. Therefore, associations between fish (or shrimp) and vegetables increase the opportunities for productive, economic, and environmental sustainability in semi-arid environments.

It is important to point out that the sustainability of production systems with brackish water requires adequate management and monitoring, especially in irrigated systems, considering the edaphoclimatic conditions in the Brazilian semi-arid region. Soil and water management techniques must be implemented, such as in situ water collection and soil cover (mulch), to increase the indicators of efficient use of water. Seasonal rains will favor the leaching of excess salts from the soil, avoiding environmental damage and losses to the farmer. However, soil fertility maintenance strategies are also recommended, such as the incorporation of crop residues, manure application, and use of wastewater sources present on farm, including treated wastewater. These techniques will contribute to the environmental sustainability of biosaline systems of family farming in semi-arid regions.

5. Conclusions

Our data show that the potential of brackish groundwater resources in the Brazilian semi-arid region depends on the set of data from the production system (salt tolerance and water demand) and the water source (water salinity and discharge rate). The joint analysis of these data shows that plant production systems with lesser water requirements (forage cactus, supplemental irrigation, hydroponic cultivation, and seedling production in nurseries) presented better results than more salt-tolerant species, including halophytes and coconut orchards.

About 41, 43, 58, 69, and 82% of wells have enough discharge rates to irrigate forage cactus (1.0 ha), sorghum (1.0 ha of supplemental irrigation), hydroponic cultivation, cashew seedlings, and coconut seedlings, respectively, without restrictions in terms of salinity. Otherwise, 65.8 and 71.2% of wells do not have enough water productivity to irrigate an area of 1.0 ha with halophytes and coconut palm trees, respectively, although more than 98.3 and 90.7% do not reach the salinity threshold for these crops. These results demonstrate that the use of quantitative and qualitative data generates more realistic information related to the potential of brackish water for agricultural purposes, and this type of evaluation should be recommended to other semi-arid regions worldwide.

Our data also indicate the need for diversification and for use of multiple systems on farms (intercropping with different plant species, association of fish/shrimp with plants, hydroponics/solar farming), to guarantee the sustainability of biosaline agriculture in the semi-arid regions, especially for family farming. However, an economic analysis of different systems should also be investigated in the future, indicating those that may result in greater net income for farmers. All these data will serve as a basis for formulating public policies aimed at the economic and social sustainability of family farming in tropical drylands.

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