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Identification of Argentinian saline drylands suitable for growing *Salicornia bigelovii* for bioenergy

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ABSTRACT

Salicornia bigelovii is an oilseed halophyte species that can be grown using saltwater in saline and coastal areas where conventional crops cannot be grown. Due to its high oil content, comparable with commercial crops, is a promising feedstock for biodiesel production. To determine the agroclimatic zoning of *S. bigelovii* in Argentina, thermal and rainfall indexes from its center of origin were taken into account and plotted for the period 1981–2010. The overlapping of the temperature and rainfall maps defined the agroclimatic zoning which determined optimal, very suitable, suitable, marginal and non-suitable areas for cultivation of *S. bigelovii* in Argentina. Subsequently, the Dryland Salinity classification of FAO was used to identify putative sites of implantation of *S. bigelovii* in moderately and strongly saline phases where soil electrical conductivity ranges from 12.4 to 22.1 mmhos/cm. Finally, the overlapping of both the agroclimatic suitability and Dryland Salinity maps afforded the agro-ecological suitability map, which showed the same five fitness classes defined in the agroclimatic zoning.

1. Introduction

1.1. *Origin, yield and uses of* Salicornia bigelovii

Annual and perennial glassworts are small succulent shrubs native to coastal marshes, salt deserts and mangroves [1–3]. They are members of three related genera *Salicornia*, *Arcthronemum* and *Sarcocornia* of the family Chenopodiaceae and share similar physiological and anato-morphological traits to survive under stressful conditions/in environments with a deficit of water and soils with a high salt content [4–6].

Salicornia bigelovii Torr (common names: glasswort dwarf, dwarf saltwort, pickleweed, sea-asparagus), original of USA and Mexico, is the most successfully cultivated annual glasswort. It is a leafless halophyte with green, jointed and succulent stems that form terminal fruit-bearing spikes, in which seeds are borne [1,7]. When the crop matures, its woody ends are covered by little seeds containing oil of good quality. The resulting paste from oil extraction may be milled to obtain

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high protein flour which could be supplied as dietary supplement for livestock, as well as fish and shrimp farms.

Because it is a facultative halophyte, it can fulfill/perform its life cycle at various concentrations of salinity [8]. Additionally, it possesses a high potential as an agro-industrial commodity because of its promise as a new oil seed resource [1,9–11]. Seeds of S. *bigelovii* may contain 26–33% of fatty acids [11–14], exceeding oil-seed levels of traditional crops such as soybean (17–21%) and cotton (15–24%) in the U.S., Brazil and Asia [12,14]. Moreover, soybean oil contains up to 6.8% of linolenic-ω3, and it is less stable due to fast oxidation when compared to S. *bigelovii* seed oil, which has only 1.4% of this fatty acid [12].

Besides exhibiting elevated tolerance to germinating in severely saline environments, S. *bigelovii* seeds exhibited an oil fraction that bore an average ratio of saturated/unsaturated fatty acids of 1:9. More specifically, the oil was composed of 66.9–79.5 wt.% linoleic-ω6 acid, 7.0–9.0 wt.% palmitic acid, 12.3–16.8 wt.% oleic acid, 1.2–3.4 wt.% stearic acid, and 1.4–2.4 wt.% linolenic-ω3 acid [1,12,15]. Interestingly, linoleic-ω6 acid was the major component, whereas linolenic-ω3 acid was the minor. The first fatty acid has medical implications, whereas the latter may result in better oil stability when compared to soybean oil that contained up to 6.8% of linolenic-ω3 [12].

Commercial development of S. *bigelovii* in Baja California Sur, Kino Bay and Santa Ana, Sonora, reveals yields of oil seed that range from 500 to 2500 kg/ha as compared to soybean that shows a minimum oil seed yield of 1000 kg/ha and a maximum of 2500 kg/ha. Interestingly, while soybean is irrigated with fresh water, *Salicornia* uses seawater [16]. Besides the United States of America and Mexico, the cultivation of S. *bigelovii* has also been successful in Pakistan, Egypt, Saudi Arabia, and the United Arabic Emirates [3,12,14,17]. The average annual seed production of this crop varies from 2.0 [11] to 3.7 tons/ha/year [18].

However, the productivity of S. *bigelovii* is limited by nitrogen availability, which not only affects its growth but also its reproductive potential [18,19]. To compensate for soil nitrogen deficiency, synthetic fertilizers have been used, but indiscriminate use of these fertilizers might severely increase soil salinity [20–23].

Plant growth promoting bacteria and mycorrhizae has been investigated as an alternative to chemical fertilizers. The inoculation of bacteria under conditions of sandy soil significantly stimulated growth and nutritional factor of *Salicornia* [24].

S. *bigelovii* accounts for other important uses as well. Several researchers have underscored the relevance of S. *bigelovii* oil as a potential feedstock of biodiesel supply for growing global demands [11,25]. Additionally, the annual rate of carbon storage by S. *bigelovii*, whose straw (25% Carbon content) would be used for carbon storage and seeds for food, is 3.2–6.2 ton/ha. This may be interpreted to mean that growing halophytes for food and folder crops could make and indirect contribution to atmospheric carbon mitigation by reducing the need for deforestation to create new cropland [26]. Other uses include the recovery of degraded soils and the recovery of areas abandoned by traditional agriculture, mainly in coastal areas [15].

An experimental crop of *Salicornia ambigua* (or *Sarcocornia perennis*) in north-eastern Brazil, irrigated with saline effluent from shrimp farms, yielded an average of 8.9 fresh weight ton/ha after three months of cultivation [2].

According to Ref. [6] S. *ambigua* (Michx.) is the most widely distributed species of this genus in South America, occurring from the coast of Venezuela to the mouth of the Plata River in Argentina [27].

1.2. Ecological requirements

S. *bigelovii* is an annual species that completes its life cycle in 205–250 days and blooms from February to April in the Southern Hemisphere. In its center of origin, the climate is BW (desert climate). The species grows at an annual average temperature of 18–20°C and annual thermal amplitude of 14°C [28]. It develops under a wide range of temperatures, which vary from 5 to 35°C although the optimal range goes from daily maximum temperatures of 20°C at the beginning of the cycle to 35°C at the end. The optimal range of daily minimum temperatures goes from 5 to 27°C [29]. S. *bigelovii* grows in areas where the annual rainfall ranges from 80 to 300 mm [29].

Rivers and Weber [30] demonstrated that S. *bigelovii* seeds were able to germinate at various temperatures (4.4, 15.5, and 26.6°C) in saline solution containing from 0% to 8.08% sea salt. At the lowest temperature, germination was delayed until the 26th day, but the final germination percentage was high in all salinities. At 15.5°C, germination was delayed until the 19th day, and the germination percentage was higher in the higher salinities. At 26.6°C, the germination was delayed 24 h and the germination percentage was higher at the lower salinities, indicating that with the exception of 26.6°C data, the maximum germination occurred at a sea salt concentration at 4.04% which is similar to sea salinity.

1.3. Salinity problems in Argentina

Salinity in soil or water is one of the major stresses that can severely limit crop production, in particular, in arid and semi-arid regions [31]. Globally 800 million hectares are affected by some degree of salinity, of which 129 million are located in South America [32].

According to FAO, Argentina is the country (after Russia and Australia) with the third largest area of land affected by processes of salinization and alkalinization, and faces a potential expansion of these non-desirable processes due to mismanagement of irrigated land [33]. The whole situation is quite complex as these processes also affect irrigated and non-irrigated arid, semi-arid and even humid areas that coincide with some of the most productive regions of the Western (Salta, Catamarca, La Rioja, San Juan, and Mendoza), Central (Tucumán, Santiago del Estero, and Córdoba) and Southern provinces (Río Negro and Chubut). During the last 40 years, one third of Tucuman's arable land was eroded by multiple degradation processes such as salinization, waterlogging and aridity. The Calchaquíes Valleys is another region with saline soils due mainly to the prevailing climatic and geological conditions. Phreatic dynamic processes in poorly drained soils also occur in sub-meridional lowlands of Santiago del Estero and in large areas of the South and East of Córdoba, affected by salinity. Drip irrigation in the region of Cuyo and deforestations of native forest in Chaco and Formosa are among other factors that have also driven soil degradation.

The process of soil salinization comes along with salt crusts, sodium humates, decreased permeability, speckled and naked soils, and presence of natric horizons, among other factors. From a biodiversity point of view, the process of soil salinization is responsible for divergence effects. On one hand, it mediates the appearance of halophytic plant communities that evolved mechanisms to survive in salty soils. On the other hand, it causes non-desirable plant symptoms such as large necrosis in photosynthetic tissue, stunting of plants, and negligible yields, that when they occur simultaneously, they may end up with the death of plant species that are unable to survive when soil salinity levels are elevated.

Halophytes, particularly *S. bigelovii*, are promising plant resources in arid coastal zones because of their tolerance to highly saline conditions [1]. These potentially important plants might be incorporated into traditional agriculture to help support the agricultural economy of those areas affected by salinity [11,34].

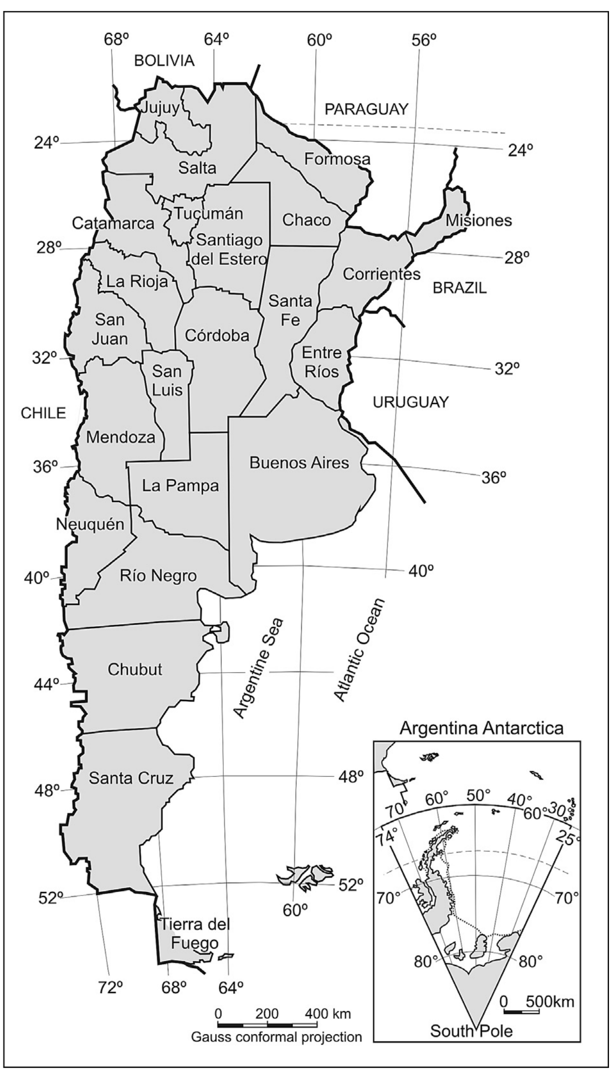

Fig. 1 – Argentina's political map.

Herein, the present research determines the agro-ecological zoning and the potential growing areas for *S. bigelovii* in Argentina.

2. Material and methods

The climate database of the Institute of Climate and Water, National Institute of Agricultural Technology (INTA) was used to calculate the agroclimatic indexes for the period 1981–2010.

To determine the putative agroclimatic zoning of *S. bigelovii* in Argentina, thermal and rainfall indexes from its center of origin and from places where the species is currently cultivated were taken into account.

To this end, the isotherm corresponding to the annual average temperature (≥18 °C) was plotted. Because the species grows during the warm semester, the plotting of average

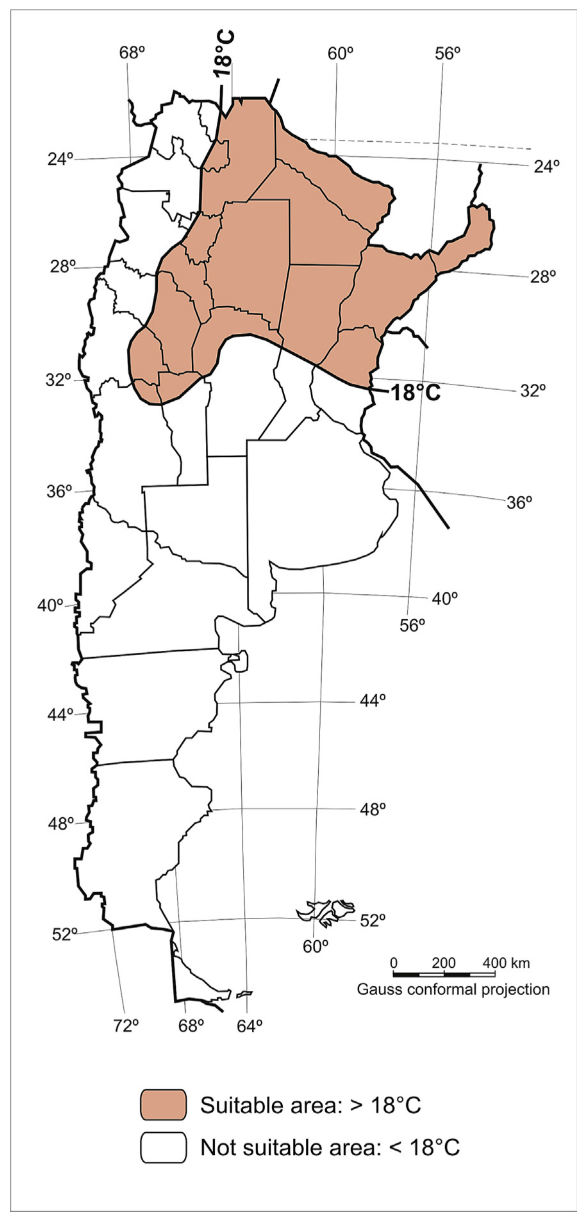

Fig. 2 – Mean annual temperature above 18 °C.

maximum temperatures during summer (≥35°C) and spring (≥20°C), as well as the plotting of the average minimum temperature (>5°C) during spring were performed.

As for rainfall requirements, country areas where annual rainfall was below 100 mm were not taken into account because the species grows in environments where the annual rainfall ranges from 80 to 300 mm.

The overlapping of the temperature and rainfall maps defined the agroclimatic zoning which determined optimal, very suitable, suitable, marginal and non-suitable areas for cultivation of *S. bigelovii* in Argentina.

To obtain the maps, we used a series of previously interpolated bioclimatic variables, which afterwards were processed with the Geographic Information System (GIS) tool of the Arc-GIS 9.3 program. Climatic interpolations were made using the "Interpolate to Raster" tool, within the "3D Analyst" extension of the Geographic Information System (GIS) of the Arc-GIS 9.3 Program, following the Ordinary Kriging interpolation method.

Agroclimatic suitability and agro-ecological suitability mapped variables were obtained from multivariable integration geoprocessing, using the "Raster Calculator" tool of the "Spatial Analyst" extension of the same program.

Based on [35] salinity classification, Drylands saline soils were plotted in Argentina, considering "moderately saline phase" when soil electrical conductivity ranges from 8 to 16 mmhos/cm and "strongly saline" when it exceeds that value, as possible sites for *S. bigelovii* implantation.

The overlap of the agroclimatic suitability map with Drylands saline soils map shows the agro-ecological zoning and defines the potential growing areas for *S. bigelovii* in Argentina for bioenergy on marginal soils.

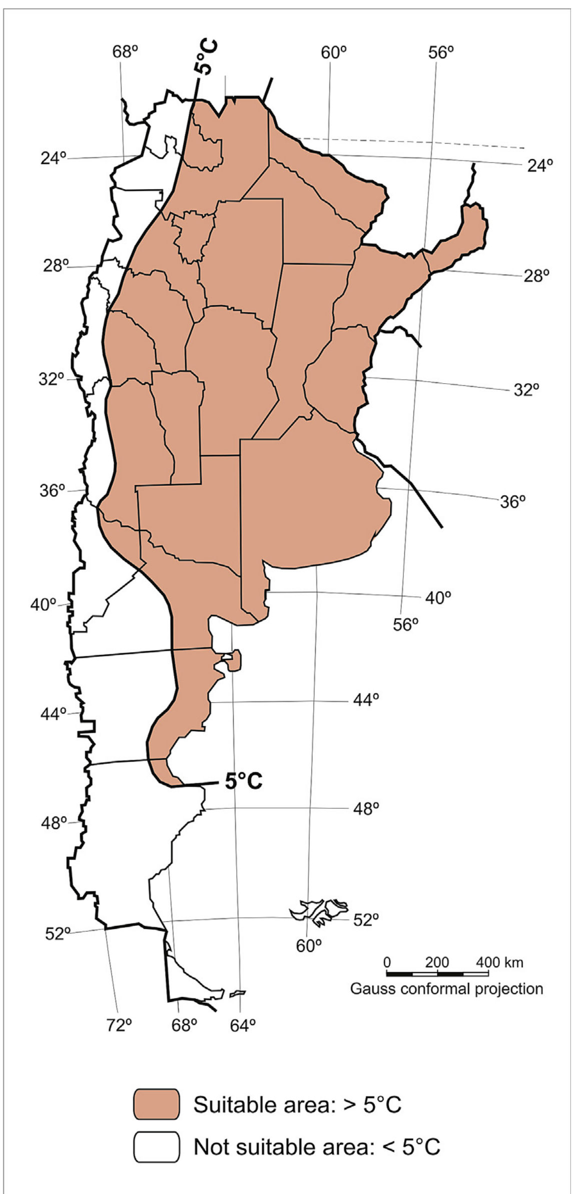

Fig. 3 – Average minimum temperature above 5°C in spring.

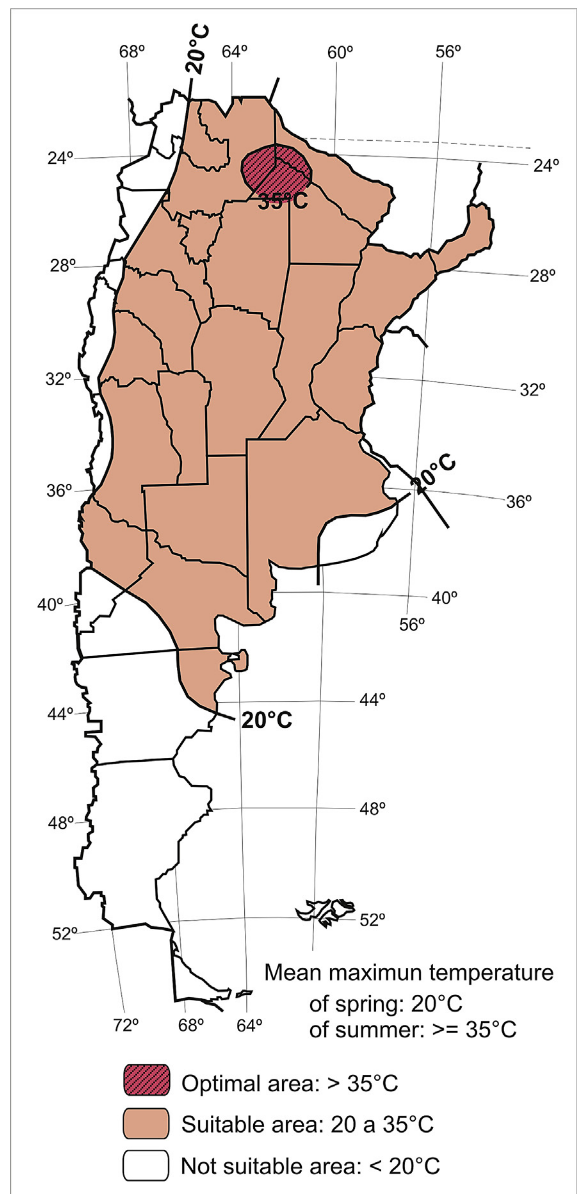

Fig. 4 – Average maximum temperature of the warm semester.

3. Results

In order to construct the classified areas with different grades of agroclimatic fitness, we included Fig. 1, Argentina's political map, with the toponymy of the provinces.

To analyze the thermal factor, the isotherm corresponding to the annual average temperature, which must be equal to or greater than 18°C, was plotted (Fig. 2). This result may be interpreted to mean that the north, the northeast and the center of the country is suitable for the crop.

Since the crop grows during the warm semester, both the average maximum and the average minimum temperatures were considered for the spring and summer times. As for spring time, the isotherm corresponding to the average minimum temperature of 5°C divided the country in two areas (Fig. 3). The suitable area for cultivation of *S. bigelovii* represented the largest part of the country and corresponded to average minimum temperature above 5°C. By contrast, the not suitable area referred to the South and West of Argentina where average minimum temperature is below 5°C (Fig. 3).

The fact that average minimum temperatures of 27°C are not even registered during the summer indicates that from a thermal point of view Argentina does not show optimal areas for growing *S. bigelovii*.

The plotting of average maximum temperatures during summer (35°C) and spring (20°C) determined optimal (>35°C), suitable (20–35°C), and not suitable areas (<20°C) for cultivation of *S. bigelovii* (Fig. 4).

Because *S. bigelovii* grows in areas where the annual rainfall ranges from 80 to 300 mm, areas of the country with less than 100 mm of annual rainfall were ruled out (Fig. 5).

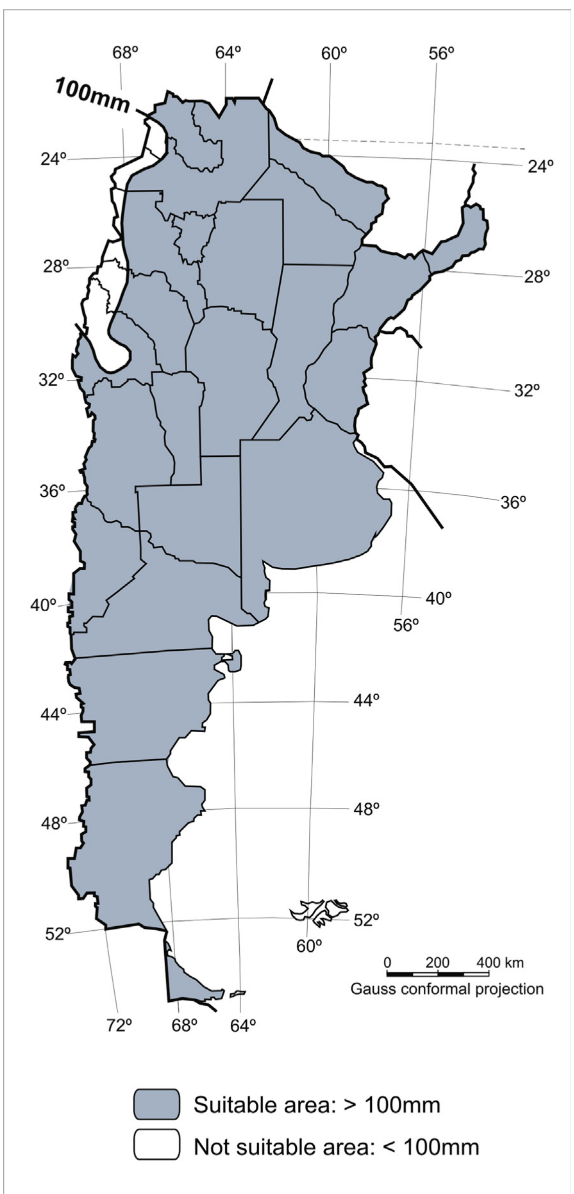

Fig. 5 – Annual rainfalls above 100 mm.

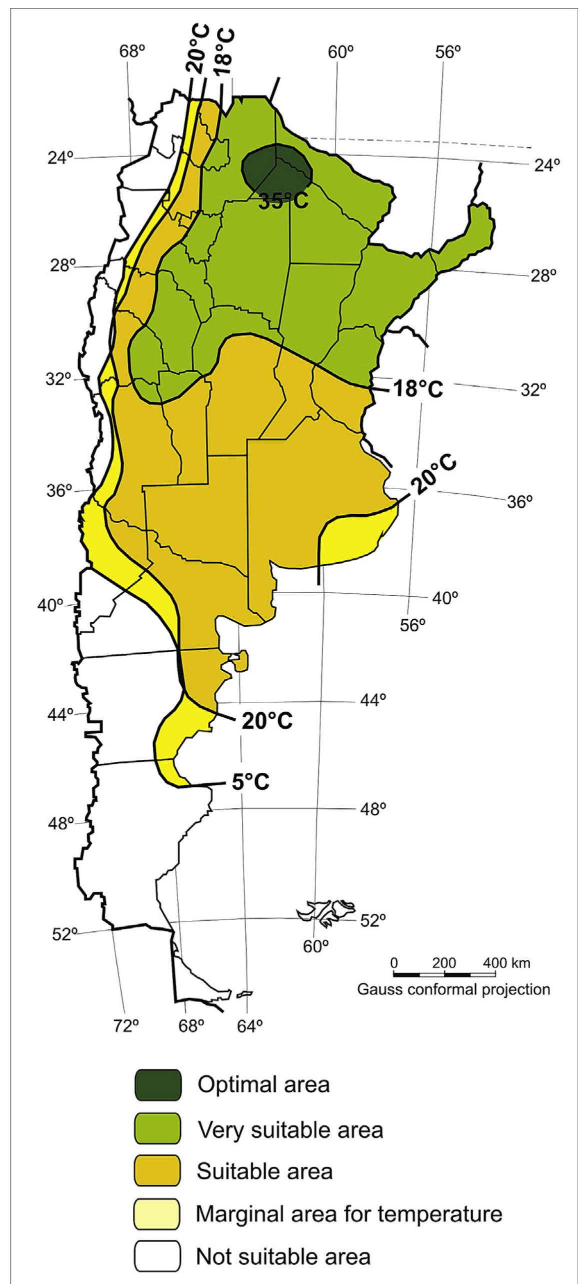

Fig. 6 – Agroclimatic suitability map.

Overlapping the preceding maps depicted in Figs. 2–5 allowed determining the agroclimatic zoning, defining optimal, very suitable, suitable, marginal and non-suitable areas for cultivation of *S. bigelovii* in Argentina (Fig. 6).

S. bigelovii may grow in environments where the soil electrical conductivity ranges from 12.4 to 22.1 mmhos/cm. This information coupled with data from the Dryland Salinity classification [35] was considered to identify putative sites of implantation of this species. Fig. 7 shows possible places for cultivation of *S. bigelovii* in a moderately saline phase where the electrical conductivity ranges from 8 to 16 mmhos/cm and in a strongly saline phase where the electrical conductivity exceeds 16 mmhos/cm.

Finally, the overlapping of both the agroclimatic suitability and Dryland Salinity maps afforded the agro-ecological suitability map, which showed the same five fitness classes defined in the agroclimatic suitability map (Fig. 8). These results identified two optimum sites in saline soils present in the provinces of Salta and Formosa, several very suitable sites in saline areas of the provinces of Salta, Formosa, Chaco, Santiago del Estero, Córdoba, San Juan, San Luis and Mendoza, and numerous suitable areas spread in the provinces of Río Negro, Chubut, Mendoza, San Luis, and South of Buenos Aires (Fig. 8).

4. Discussion

In this research, information from the Dryland Salinity classification of FAO was complemented with data from the agroclimatic suitability map to afford the agro-ecological

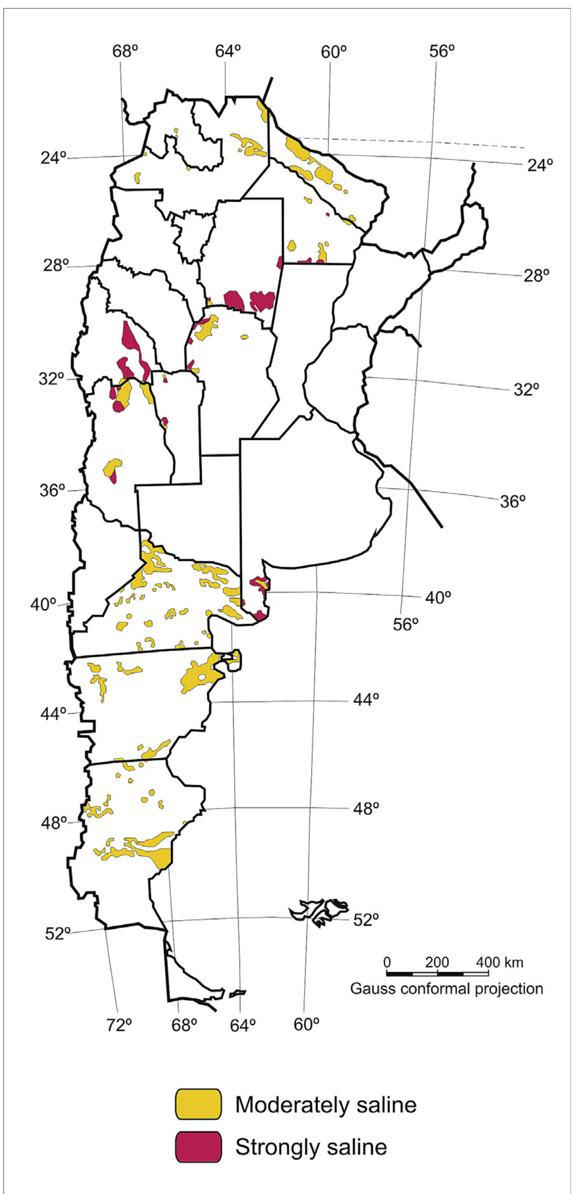

Fig. 7 – Saline drylands. Source: FAO (2008).

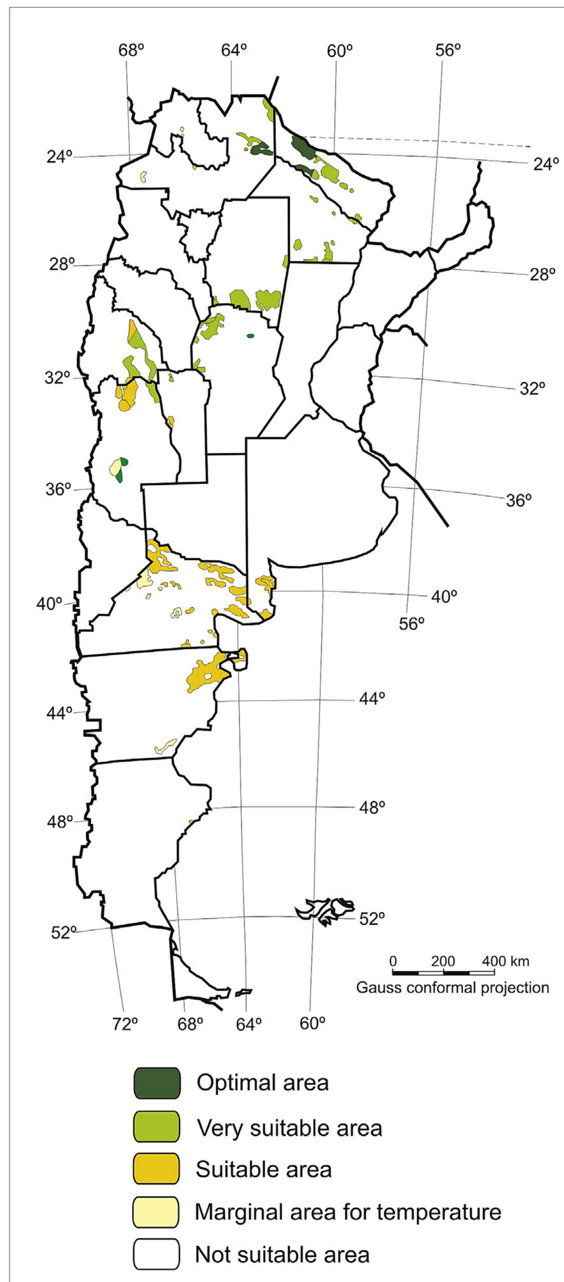

Fig. 8 – Agro-ecological suitability map.

suitability map for the cultivation of S. *bigelovii* in Argentina. The zoning of the agro-ecological suitability map of S. *bigelovii* broke down the country into five areas, three that may be grouped as suitable, one marginal due to temperature, and one non-suitable for growing this species (Fig. 8). In accordance with the temperature requirements of S. *bigelovii*, the optimal areas for the growth of this culture were concentrated in the North and the very suitable areas were spread in the central part of the country (Fig. 8).

The agro-ecological suitability map of S. *bigelovii* provided further evidences that indicate that this crop does not compete for soil occupancy with traditional agricultural crops and forestry, as seeds of this species may germínate and its seedlings may grow in moderately to strongly saline soils [30].

5. Conclusions

The existence of a large area with suitability for the cultivation of S. *bigelovii* has been demonstrated. The cultivation of this species does not reveal neither direct nor indirect land-use change of traditional agricultural crops nor forestry since S. *bigelovii* may be implanted in moderately to strongly saline soil and may be irrigated with seawater wells or saline aquifers. Furthermore, extensive culture may lead to diminishing salinity levels, improving nutrient availability and storage of carbon in the soil while preserving the environment.

The coastal deserts or inland could be irrigated with seawater wells or saline aquifers, to grow S. *bigelovii* for food, forestry, animal feed and biofuels. The dwarf glasswort is a promising oilseed crop (biodiesel) for Argentina, due to its high oil content comparable with commercial crops. It may also be a promising biomass source for ethanol production.

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