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Salvadora persica agro-ecological suitability for oil production in Argentine dryland salinity

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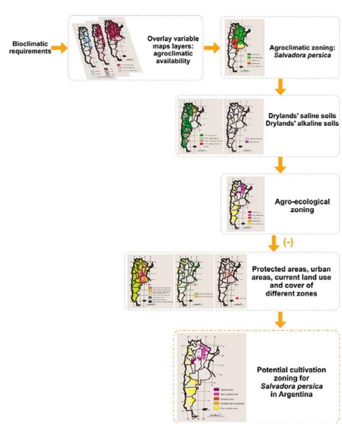
HIGHLIGHTS

- The authors designed an agro-ecological zoning model for *S. persica* in Argentina.
- To obtain the maps, bioclimatic and edaphic variables were processed with the Arc-Gis.
- Protected and urban areas, lands currently destined for other uses, were subtracted.
- Optimal, very suitable, suitable, marginal and non-suitable areas were delimited.
- This work is the first research study concerning its introduction in Argentina.

GRAPHICAL ABSTRACT



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ABSTRACT

One of the major causes of crop stress is soil or water salinity. Thus, selection of the best species for cultivation in semiarid and arid climates is fundamental.
Salvadora persica is an evergreen perennial halophyte that can grow under extreme conditions, from very dry environments to highly saline soils.
Based on international bibliography, the authors outlined an agro-ecological zoning model to determine the potential cultivation zones for *S. persica* in Argentina. This model may be applied to any part of the world, using the agro-ecological limits presented in this work. All the maps were developed by the implementation of a geographic information system (GIS) that can be updated by the further incorporation of complementary information, with the consequent improvement of the original database.
The overlap of the agroclimatic suitability map on the drylands' saline soils and the drylands' alkaline soils maps, determined the agro-ecological zoning. Since some areas in the agro-ecological zoning can overlap with land that is already assigned for other uses, protected areas, current land use/cover of the different zones, and urban areas maps were incorporated into the GIS and subtracted by a mask. This resulted in the delimitation of "potential cultivation zoning", thus avoiding possible conflicts surrounding the use of land and making the agro-ecological zonation more efficient.

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There is a broad agro-ecological zone for cultivation of *S. persica* that extends from Northern Argentina to approximately 41° South latitude, under dry-subhumid to semiarid climates. Lands classified with different degrees of suitability in the potential cultivation zoning could be used for production of this species for energy purposes on lands that are either unsuitable for food production or currently assigned for other purposes.
This paper represents pioneering work since there are no previous studies concerning the introduction of *S. persica* in Argentina.

1. Introduction

Soil and water salinity constitute the two most important factors that limit agricultural activity in arid and semiarid regions. It has been estimated that nearly 1 billion ha of arid and semiarid areas of the world are affected by salt (Gurbachan and Dagar, 2009). These soils usually remain barren due to salinity or water scarcity, and the crops that are eventually grown on them must receive complementary irrigation. The situation is aggravated by the fact that more than half the world's groundwater supply is saline and its contamination is a growing problem.

The conversion of land use through several damaging practices, such as deforestation, excessive irrigation, poor drainage and use of brackish water for irrigation is known as anthropogenic or secondary salinization, and it poses severe problems in arid and semiarid regions. In general, halomorphism processes (salinization, alkalinization and sodicity) are increasing worldwide due to the mishandling of irrigated soils.

In a FAO–UNESCO study of these processes, Argentina ranked third in the world, after Russia and Australia (Taboada and Lavado, 2009). The recovery of these soils for the cultivation of commercial crops is too expensive for the majority of the countries affected.

According to FAO (2008), there are currently 400 M ha of salinized land, and a similar area is affected by sodicity. Approximately 20% of the 280 M ha irrigated land in the world is affected by secondary salinity (Yamaguchi and Blumwald, 2005). Secondary salinization is a particularly severe problem in developing countries of South America (Argentina, Bolivia and Peru).

The world faces a diminishing supply of farmable land and an increasing demand for food, fiber and energy. Within this scenario, it becomes imperative to search for salt tolerant species (halophytes) that can be grown in the soils described above, both in rainfed and irrigated agriculture systems. These species should have high economic value, and in this respect, food, oilseed and petro-crops are particularly interesting. Plants with proven or potential medicinal value are also attractive. Furthermore, they must not only be tolerant to salinity and drought stresses but also well adapted to the local agro-climate (Gurbachan and Dagar, 2009).

This work's target consisted in defining the agro-ecological suitability of the Argentine drylands' halomorphic soils to produce oil and co-products from *Salvadora persica*.

1.1. Characteristics of S. persica

S. persica L. is an evergreen small tree commonly known as *mustard tree*, *salt bush*, *siwack*, *miswack*, *tooth brush tree*, etc. It belongs to the family Salvadoraceae and has a wide geographic distribution, ranging from Rajasthan, Nepal and Malaysia in the east through Pakistan, Iran, Iraq, Saudi Arabia and Egypt to Mauritania in the West, and from North Africa through Sudan, Ethiopia, and Central Africa to Southwestern Africa (Wu et al., 2001). This species exhibits variations in its distributional behavior in different countries. This may be attributed to modifications in water resources, climatic factors, edaphic variables and anthropogenic pressures along the elevation gradient (Hassan et al., 2010).

The tree can reach a height of 6–7 m. Flowers are small, greenish yellow in axillary and terminal panicles, sessile or sub-sessile, bisexual and tetramerous (Kumar et al., 2012). The fruit is spherical, succulent, with a diameter of 5–10 mm and when it ripens its color ranges from rose to scarlet. According to Kumar et al. (2012), to achieve high seed settings and seed oil content, harvesting should take place 3 months after seed setting. There are about 3400 seeds/kg. Oil-rich seeds of *S. persica* cannot be stored for long periods (Kumar et al., 2012).

S. persica is one of the most productive halophytic species known. It can yield up to 20 tons/ha of biomass on seawater irrigation, equivalent to conventional crops (Glenn et al., 1999). Agro-technology has been developed for *siwak* cultivation on highly saline soils with saline water irrigation.

Studies carried out by the Central Soil Salinity Research Institute (CSSRI, Karnal, India) revealed that 5-year old *siwak* plantations can have oil yields of up to 1.800 kg/ha. Plantations can yield 3.5 ton seeds/ha/year, and they have a lifespan of up to 100 years. This is in agreement with the results obtained by Rao et al. (2004). Since *S. persica* has not yet been introduced in Argentina, there are no data regarding its adaptation or yields in our country.

1.2. Uses

S. persica is a non-traditional oilseed tree crop that is valuable for a wide variety of industries. The oil has a disagreeable odor that disappears on purification. The seed contains 40–45% of non-edible oil, rich in lauric and myristic acids. Reddy et al. (2008) reported that, although the species can grow in both saline and alkaline soils, significantly higher yields, propagation and seed production were observed in plants cultivated on saline soils in comparison with alkaline ones. However, they did not observe significant differences in the oil content of seeds from plants cultivated in saline or alkaline soils.

The oil is used in the soap, candle and detergent industries. Furthermore, it also has enormous potential for biodiesel production (Bringi, 1987). The lubrication properties of biodiesel from *S. oleoides* and its blends have been studied thoroughly. Bhatnagar et al. (2006) concluded that the addition of biodiesel improved the lubricity and reduced wear scar diameter, even at a 5% blend.

Further chemical analysis of *S. persica* has demonstrated the presence of a large number of compounds, many of them with proven or potential pharmacological activities. Among them, the following are conspicuous: b-sitosterol and m-anisic acid, chlorides, salvadourea, pyrrolidine, pyrrole, and piperidine derivatives (Galletti et al., 1993), glycosides, such as salvadoside and salvadoraside (Kamel et al., 1992; Darout et al., 2000), flavonoids, including kaempferol, quercetin rutin and a quercetin glucoside (Abdel-Wahab et al., 1990). The roots and bark have large quantities of alkaloids, such as salvadorine and trimethylamine (Dorner, 1981; Al lafi and Ababneh, 1995).

The literature review revealed abundant claims as to the value of *S. persica* in the treatment of a large spectrum of diseases (Bhandari, 1990; Khare, 2007; Iyer and Patil, 2012; Kumar et al., 2012; Chaurasia et al., 2013). Seed oil is applied on the skin in rheumatism (Atassi, 2002). Leaves are also employed in traditional medicine to relieve cough and treat asthma, scurvy, rheumatism, piles, and other diseases. Farooqi and Srivastava (1968) isolated benzyl-isothiocyanate (BITC) from roots, a compound that has virucidal activity against Herpes simplex virus 1 (Al-Bagieh, 1992) and broad-spectrum bactericidal activity (Pulverer, 1969).

Currently, however, its main value lies in the field of dental hygiene. The applications found in dental care are not unexpected, since for many years Islamic communities have used its fibrous branches, called "*siwak*", as toothbrushes. The positive effects observed on dental hygiene are due mainly, but not only, to the antimicrobial effects of many of the compounds mentioned above. For example, antibacterial activity has been attributed to sulfur compounds and several distinct alkaloids (Almas and Al-Zeid, 2004). Vitamin C was found to help in tissue healing and repair (Almas, 1993). The mildly bitter taste of the essential oils in *siwak* stimulates the flow of saliva, which acts as a buffering agent. The astringent effect of tannins may help reduce clinically detectable gingivitis (Gazi et al., 1992). Salvadorine may exert a bactericidal effect and stimulate the gingiva (Almas, 1993). Silica acts as an abrasive and helps to remove stains from tooth surfaces (Al lafi and Ababneh, 1995). However, the main value of siwak is primarily its mechanical cleaning action (Akpata and Akinrimisi, 1977).

S. persica is also a valuable food, and in Eastern tropical Africa the leaves and tender shoots are eaten as vegetables, usually in salads, and used in the preparation of a sauce. In the Arabic Peninsula, there are forest plantations implemented with *S. persica* that are integrated into windbreaks in order to protect agricultural and horticultural cultivars. Furthermore, *S. persica* plantations can be helpful in recovering sand dune habitats and saline soils. Phyto-remediation is also feasible because it can remove salt from soil, e.g. it has the potential to remove substantial amounts of sodium from soil (up to 25 dS m^{-1}) (Gurbachan and Dagar, 2009).

The wood is sometimes used for firewood and charcoal, but not for cooking meat because it leaves an unpleasant taste. The resin secreted by the tree can be used to manufacture varnish (Kumar et al., 2012).

2. Materials and methods

2.1. Study area

The area studied was the Argentine Republic. The country borders to the North with Bolivia and Paraguay; to the South with Chile and the Atlantic Ocean; to the East with Brazil, Uruguay and the Atlantic Ocean and to the West with Chile.

As a result of its vast territory, Argentina presents exceptional climatic diversity. Various geographic factors influence the climatic characteristics of the different regions. One of these is latitude: the Argentine Republic is characterized by its great latitudinal development: 21°46′ in the North to 55°03 in Cape San Pio, in the South. The extreme eastern limit of the country is located at 53°38′W, in the town of Bernardo de Irigoyen.

2.2. Ecological requirements

According to Duke (1983), there are several climate zones fit for *S. persica*, including Tropical wet and dry (Aw), Desert or arid (Bw), Steppe or semiarid (Bs) and Subtropical dry summer (Cs). The species extends from the latitudes 20° to 40°. The plant can be found up to 1800 m above the sea level (FAO Ecocrop, 1993–2007).

Siwak thrives in temperatures ranging from 12 to 42 °C and annual rainfalls of 200 to 1500 mm. The optimal ranges are 15° to 30 °C with 300 to 700 mm of rain (FAO Ecocrop, 1993–2007). It is extremely resistant to drought and it is frost-tolerant, surviving in temperatures as low as −10 °C.

The species grows well in saline environments and can tolerate salinity levels up to 50 dS m^{-1}, waterlogging conditions and saline coastal spray. The plants can also be watered with saline water with electrical conductivity (EC) levels up to 15 dS m^{-1}. It can tolerate a wide range of pH values: from 6.5 (World Agroforestry Centre) to 10.0 (Gurbachan and Dagar, 2009). *S. persica* L is one of the species most tolerant to waterlogged saline soil and can be raised successfully in soils with salinity levels of EC 30–40 dS m^{-1} (Gurbachan and Dagar, 2009).

Rao et al. (2004) found that the seed yield was dependent on soil salinity. When comparing soils with salinity levels as high as 55–65 dS m^{-1} with ones that had 25–35 dS m^{-1}, the yield declined by 40–47%.

S. persica is a facultative halophyte, exhibiting remarkable flexibility since it can be cultivated in saline and non-saline soils. In addition, the textures of these soils can be very versatile, ranging from sandy to clay. As a result, it can be considered a drought and salt-tolerant species. Furthermore, it counteracts the advancement of desertification as an effective soil binder (Zodape and Indusekhar, 1997), thus fulfilling an important ecological function.

2.3. The agroclimatic zoning

Every plant is sensible to weather conditions. In order to satisfy its physiological requirements, each plant has a minimum as well as a maximum demand from the climate. Beyond such limits, it is negatively affected. The range between these two values represents the energetic level the plant needs for its physiological complex to work efficiently. This range is called "ideal temperature" (Ometto, 1981). Agroclimatic zoning consists in the division of an area of land into climatic resources units and identifies areas with different potential yields, according to the environmental conditions. These units have a unique combination of climatic characteristics, which in turn specify the potentials and constraints for land use. Then, agroclimatic zoning can be understood as the division of an area according to the favorability for agriculture. To establish the siwak-growing zones, the identification of its requirements, limits and bio-meteorological tolerance and conditions is fundamental. The climatological characteristics of native areas and the regions of successful cultivation around the world were first taken into consideration. Afterwards, the resulting bioclimatic indicators were extrapolated to the Argentine territory. Growth aspects, such as development and death chances by excess or deficiency, were examined.

Geographical location, mean annual rainfall and temperature records area available (for the period 1981–2010) from meteorological and agrometeorological stations within the study area were also taken into account.

The bioclimatic variables studied were average annual temperature, absolute minimum temperature and annual rainfall. These were obtained by interpolating the data collected in the 125 meteorological stations around the country that belong to the National Meteorological Service. From the available database, geographical limits were mapped for the different variables that define different aptitude classes: optimal, very suitable, suitable, marginal and non-suitable zones.

To analyze the thermal regime, the average of the annual temperatures was considered. When the average was lower than 12 °C, the area was rated as non-suitable and in the 12 to 15 °C range it was labeled as suitable, while temperatures ranging from 15 to 30 °C qualified it as an optimal area.

Although Argentine territory extends towards the Tropic of Capricorn (23°27′S), it lacks tropical climates. Therefore, when tropical species are exploited, special care must be taken to avoid damage by frost. The absolute minimum temperature, which is by definition the lowest recorded temperature that occurs at least once every 30 years, was mapped independently. The area was considered non-suitable when the absolute minimum temperature was lower than −10 °C, because the frost not only inhibits fructification, but it is also lethal to the species.

In order to analyze the moisture regime, the isohyets that corresponded to the annual rainfall were considered. Optimal areas were the ones receiving rainfalls in the 300–700 mm range. The areas with values below 300 mm were rated non-suitable and those above 700 mm, suitable.

Finally, the agro-climatic zoning (obtained overlaying the cited maps above) shows the areas in the country where this species may be grown with success probability under rainfed conditions.

Five classes of agroclimatic suitability areas were defined: optimal, very suitable, suitable, marginal and non-suitable. Table 1 shows the agroclimatic indices that define each class of agroclimatic suitability. It

Table 1
Classes of agroclimatic suitability and limits for each class.

	Annual rainfall (mm)	Annual temperature (°C)	Absolute minimum temperature (°C)
Optimal area	300–700	15.0–30.0	> −10
Very suitable	>700	15.0–30.0	> −10
Suitable area	>700	12.0–15.0	> −10
Marginal area	>300	>12.0	< −10
Non suitable area	<300	<12.0	< −10

is important to highlight that the non suitable areas present two or more of the constraints indicated in Table 1.

To obtain the maps, a series of previously interpolated bioclimatic variables were used, which were processed afterwards 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 same program, following the Ordinary Kriging interpolation method.

2.4. The agro-ecological zoning

Agro-ecological zoning defines zones on the basis of combinations of soil and climatic characteristics. The particular parameters used in the definition focus attention on the climatic and edaphic requirements of crops and on the management systems under which the crops are grown. Each zone has a similar combination of constraints and potentials for land use, and serves as a focus for the targeting of recommendations designed to improve the existing land-use situation, either through increasing production or by limiting land degradation (FAO, 1996).

In saline soils, sodium cations are prevalent, and have electrical conductivity values greater than 4 dS m^{-1}. The dominant anions are usually soluble chloride and sulfate. Based on the FAO (2008) salinity classification, drylands' saline soils of Argentina were plotted and the possible sites for *S. persica* implantation identified were the "moderately saline phase", with soil electrical conductivity ranging from 8 to 16 dS m^{-1} and the "strongly saline phase", with values exceeding the preceding range. It is important to remark that this species can be grown successfully in saline soils with levels of EC 30-40 dS m^{-1} (Gurbachan and Dagar, 2009).

Sodic soils have high pH levels (greater than 8.5, sometimes reaching values of 10.7) with a high Exchangeable Sodium Percentage (>15). Sodic soils have high concentrations of free carbonate and bicarbonate and excess of sodium on the exchangeable site of clay particles. They are also deficient in nitrogen, phosphorus and zinc. Likewise, based on the FAO (2008) alkalinity classification, drylands' alkaline soils of Argentina were plotted, considering the moderately alkaline soils (Exchangeable Sodium Percentage ranges from 15 to 40%), and strongly alkaline soils (when 40% is exceeded). These locations were targeted as possible sites for *siwak* cultivation. As mentioned above, this species can inhabit areas with a wide range of pH values from 6.5 to 10.0 (neutral to strongly alkaline).

It is important to recall that FAO (1996) classifies as drylands the ones that have dry-subhumid, semiarid and arid climates.

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

The overlap of the agroclimatic suitability map on the drylands' saline soils map and drylands' alkaline soils map shows the agro-ecological zoning, and defines the agro-ecological zones for *S. persica* for oil production on halomorphic soils. However, since some areas in the agro-ecological zoning can overlap with land that is already assigned for other uses, such as protected areas, areas with traditional crops, urban areas, etc., these were subtracted or "masked".

Competition for areas with different current land uses has to be seriously considered when analyzing the possible expansion of the crop, and differentiating those areas that have some degree of legal protection is crucial. Thus, the map corresponding to "Protected areas" (SAyDS, N/D) was incorporated into the GIS. In addition, the "Current land use and cover of the different zones" were taken into consideration. To this end, the Eco-regions map developed by INTA (2009), using satellite images (Landsat and MODIS) and based on the Land Cover Classification System of FAO (Di Gregorio and Jansen, 1998) was used. The map of "Urban areas" (IGN, 2013) was also included; and the federal, provincial, and municipal areas were subtracted through a mask.

The delimitation of the "potential cultivation zones" was obtained by superimposing the previous layers on the agro-ecological zoning.

3. Results and discussion

In order to construe the classified areas with different grades of agro-climatic fitness, it was included as Fig. 1 Argentina's political map, with the toponymy of the provinces.

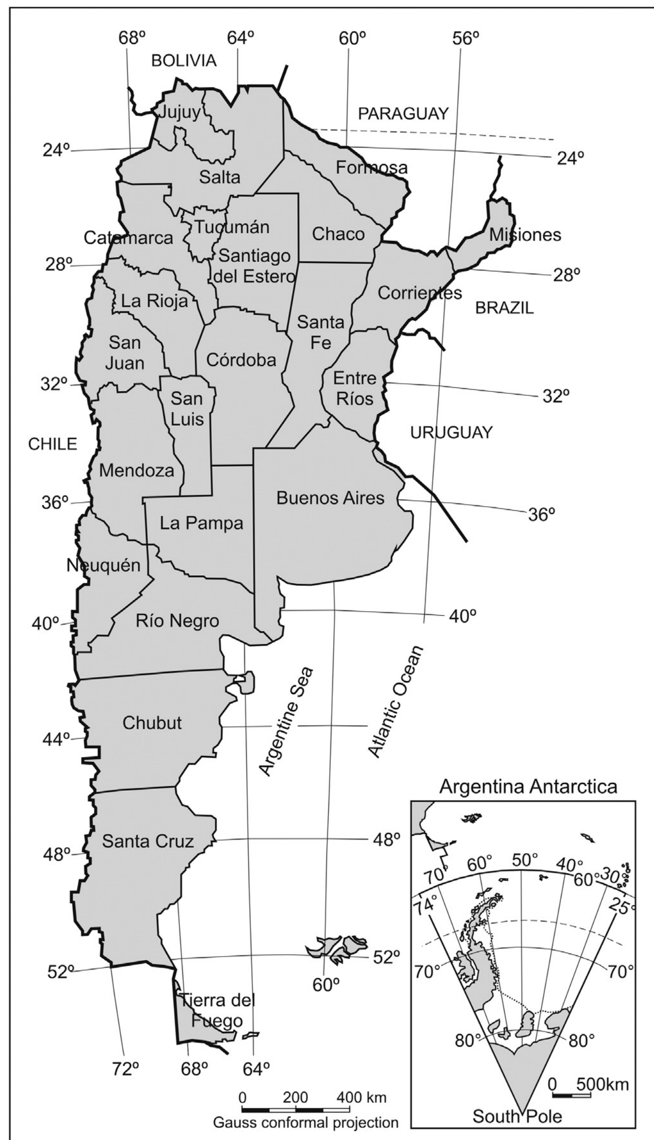

Fig. 1. Political map of Argentina.

In Fig. 2, the moisture regions can be observed. For this purpose, mean annual isohyets of 300 and 700 mm were included. The suitable areas, with annual rainfall higher than 700 mm, comprise the Mesopotamia Region, the Chaco-Pampean prairie and the Northwest Region of Argentina. The Northwest Region receives seasonal rainfall during the warm semester. These are called monsoon regimes because they are similar to the ones in India, but in a lesser magnitude. On the other hand, the Mesopotamia and the Chaco-Pampean prairie receive humid winds due to the influence of the South Atlantic anticyclone. The optimal areas receive 300 to 700 mm of annual rainfall. These surround the Northwest region and span the center of Argentina from the south of Tucumán to the south of Buenos Aires and Rio Negro.

The moisture provided by the South Atlantic anticyclone diminishes gradually as the mass of humid air moves to the West. Consequently, the annual amount of rainfall also decreases in that direction. Fig. 2 also shows another area located in the west and to the south of Parallel 33° that also receives 300 to 700 mm of annual rainfall. In that region, the height of the Andes Mountain Range declines and transversal valleys appear. This configuration promotes the advection of humid air from the South Pacific anticyclone. At the same time, the transport of moisture from the west to the east decreases. Annual amounts of precipitation lower than 300 mm are determinants of non-suitable areas.

In Fig. 3, the thermal regions can be observed. The optimal area comprises the Mesopotamia and the Northwest Region, the north and the center of Argentina, including the center of the provinces of Buenos

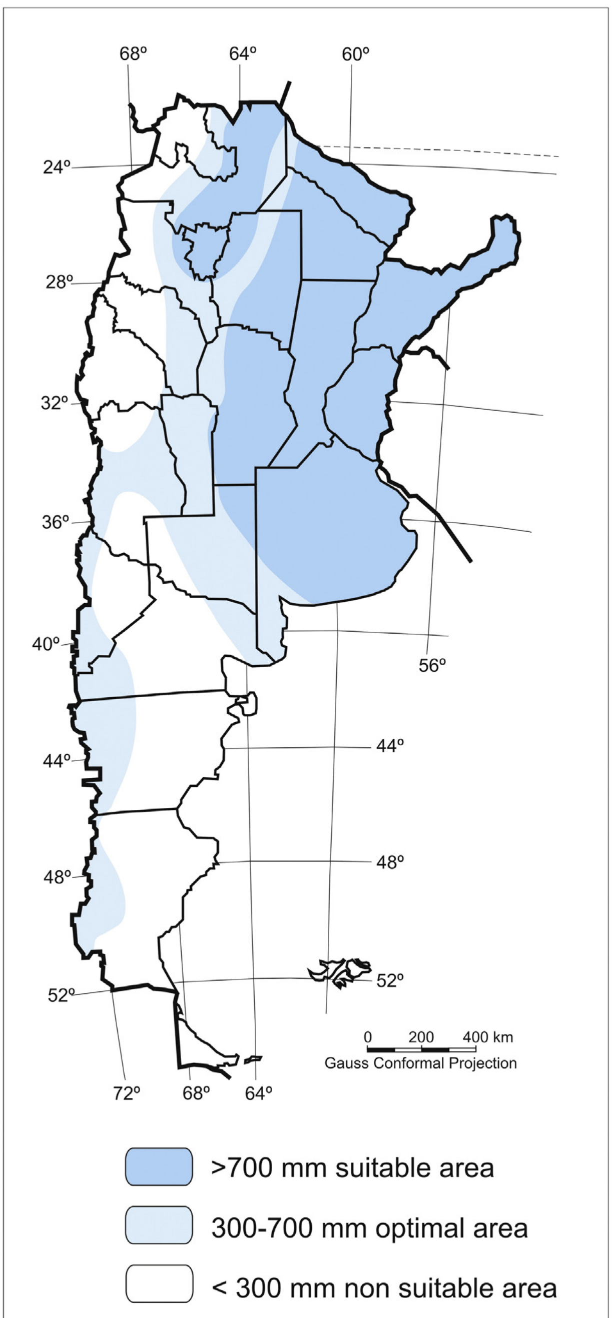

Fig. 2. Average annual rainfall (mm).

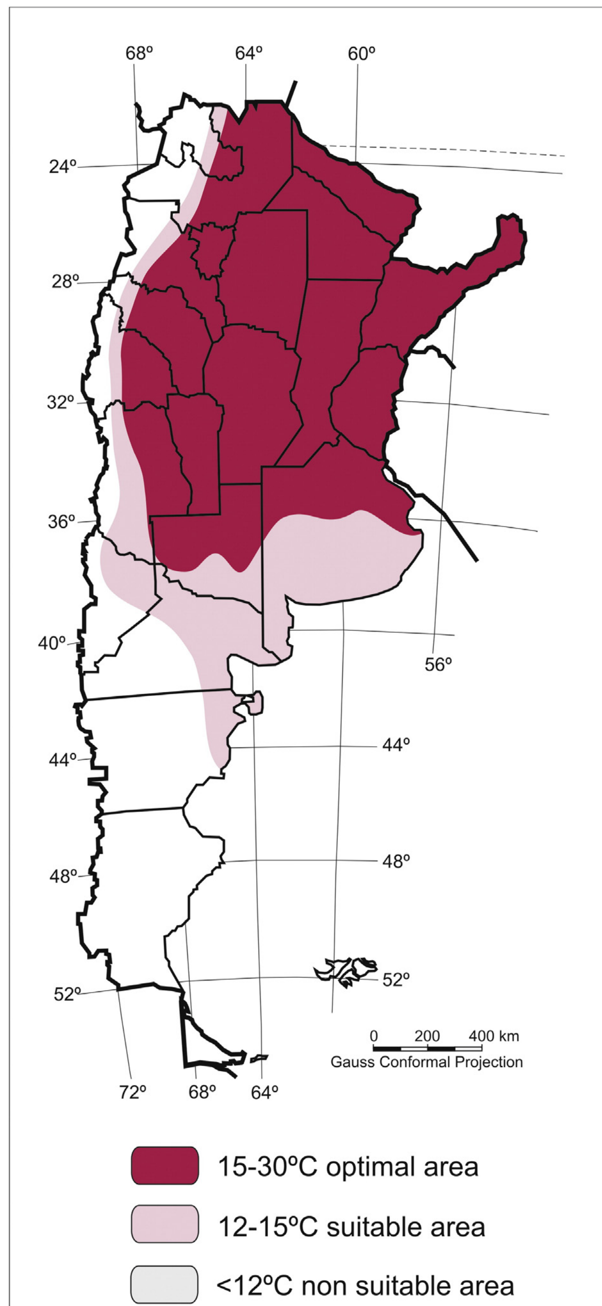

Fig. 3. Average annual temperature (°C).

Aires and La Pampa. The suitable area extends west and south of the optimal one, and involves the west of Mendoza, the east of Neuquén, the south of La Pampa, the center and south of Buenos Aires, and part of Rio Negro and Chubut.

Fig. 4 shows the absolute minimum temperature of −10 °C that represents the minimum lethal temperature for *siwak*. These low temperatures have a recurrence of 1 time every 30 years. The region of the country where the absolute minimum temperature is lower −10 °C is incompatible with the commercial cultivation of *S. persica*. Suitable areas cover the north, the northeast, part of central region of the country and the province of Buenos Aires.

Agro-climatic zoning allows the identification of areas with different potential yields, according to their environmental conditions. Fig. 5 presents the agroclimatic suitability map, where the 5 areas, classified according to their suitability, can be observed. The regions pertaining to these areas are detailed below:

Optimal areas are those where the average annual temperature ranges from 15 to 30 °C, the annual rainfall is in the range 300 to 700 mm and the absolute minimum temperature lies above −10 °C. They are found north of San Luis, south of La Rioja and Catamarca, west of Cordoba, center of Santiago del Estero, west of Chaco and Formosa and east of Salta.

Very suitable areas have average annual temperatures ranging from 15 to 30 °C, annual rainfalls higher than 700 mm and absolute minimum temperature above −10 °C. These areas cover the east of Salta, Jujuy

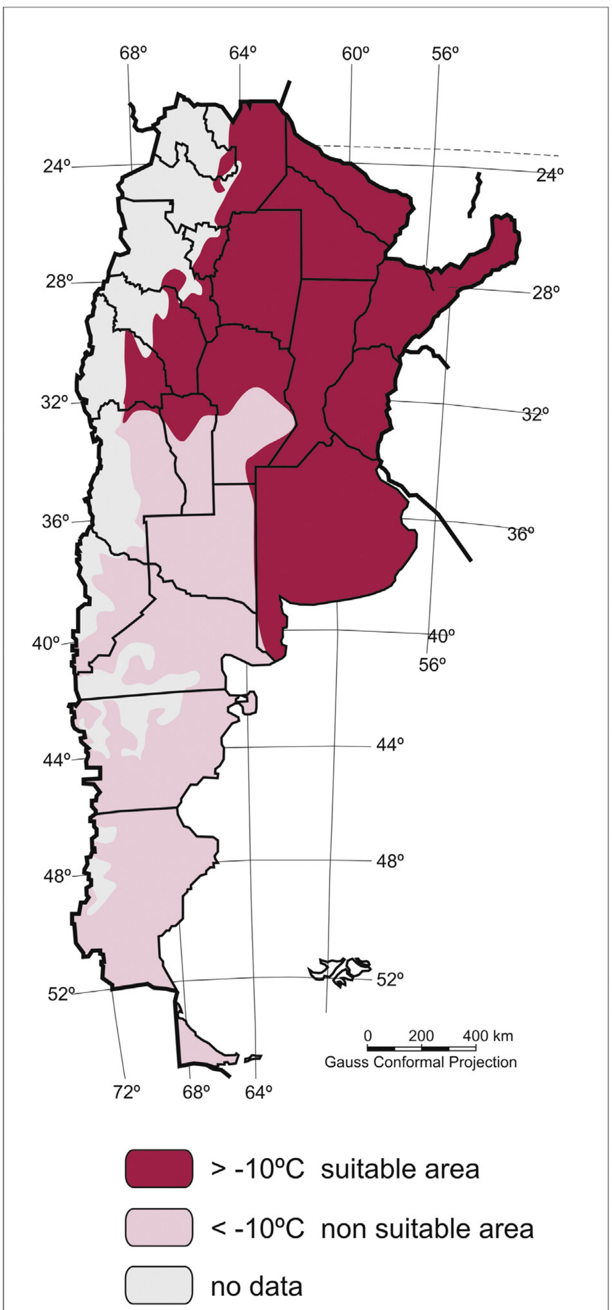

Fig. 4. Absolute minimum temperature (°C).

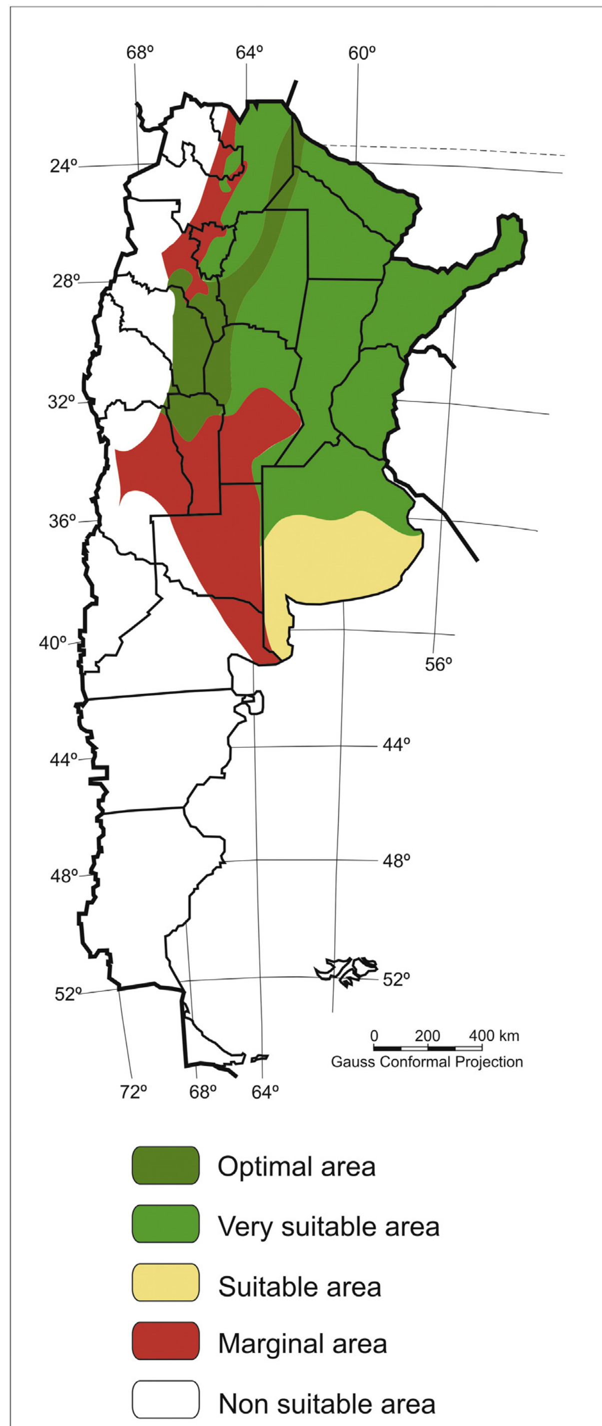

Fig. 5. Agroclimatic suitability for *S. persica*.

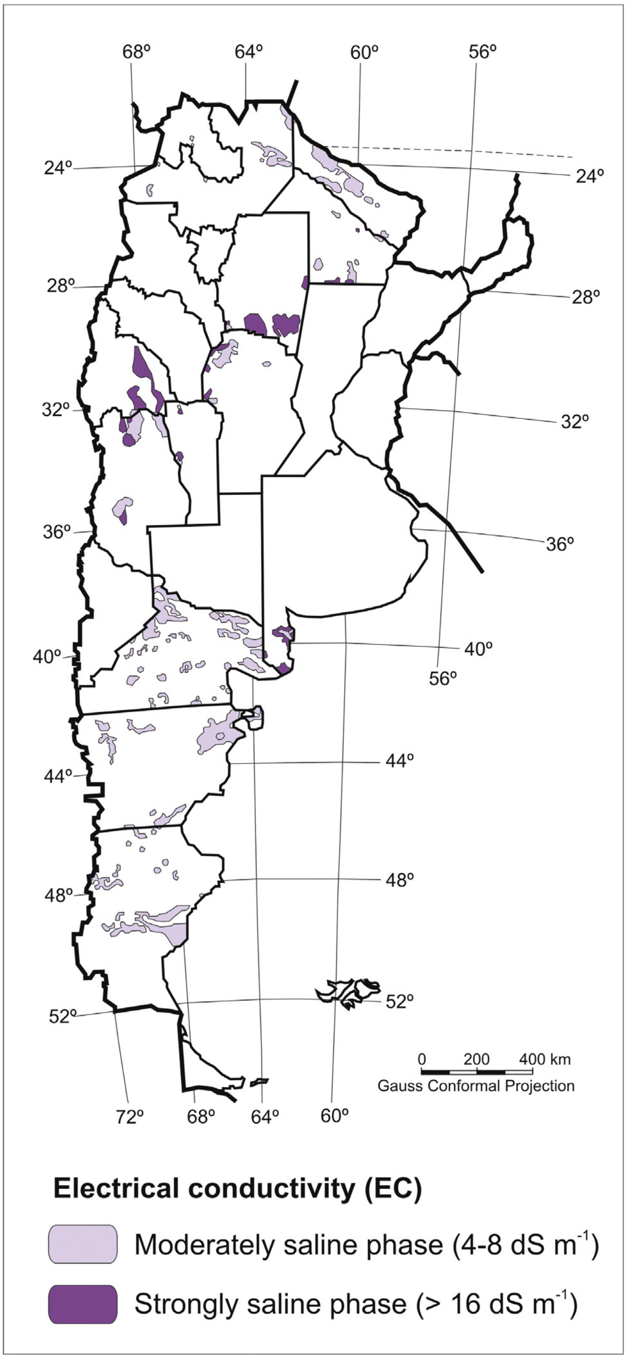

Fig. 6. Salinity of soils in Argentinean drylands (FAO, 2008) in dry regions (arid, semiarid and dry-subhumid climates, according to FAO (1996)).

and Tucumán; almost all Formosa; Chaco; the north and center of Cordoba; Santa Fe; all the Mesopotamia Region and the north and center of Buenos Aires.

Suitable areas have average annual temperatures ranging from 12 to 15 °C, annual rainfalls are higher than 700 mm and the absolute minimum temperature is above −10 °C. Suitable areas are located only in the center and south of Buenos Aires.

Marginal areas are those where the average annual temperatures are higher than 12 °C, the annual rainfall is above 300 mm and the absolute minimum temperature is below −10 °C. These extend to the west of the very suitable areas.

Non-suitable areas have a combination of two or more of the following variables: average annual temperature below 12 °C, the annual rainfall is lower than 300 mm or the absolute minimum temperature is below −10 °C.

When the agroclimatic suitability map (Fig. 5) is superimposed on the drylands' salinity map (Fig. 6) and drylands' alkalinity map (Fig. 7), the overlapping regions determine the Agro-ecological zoning (Fig. 8).

Agro-ecological zoning consists in the division of an area of land into smaller units that have similar characteristics in relation to land suitability, potential production and environmental impact. Fig. 8

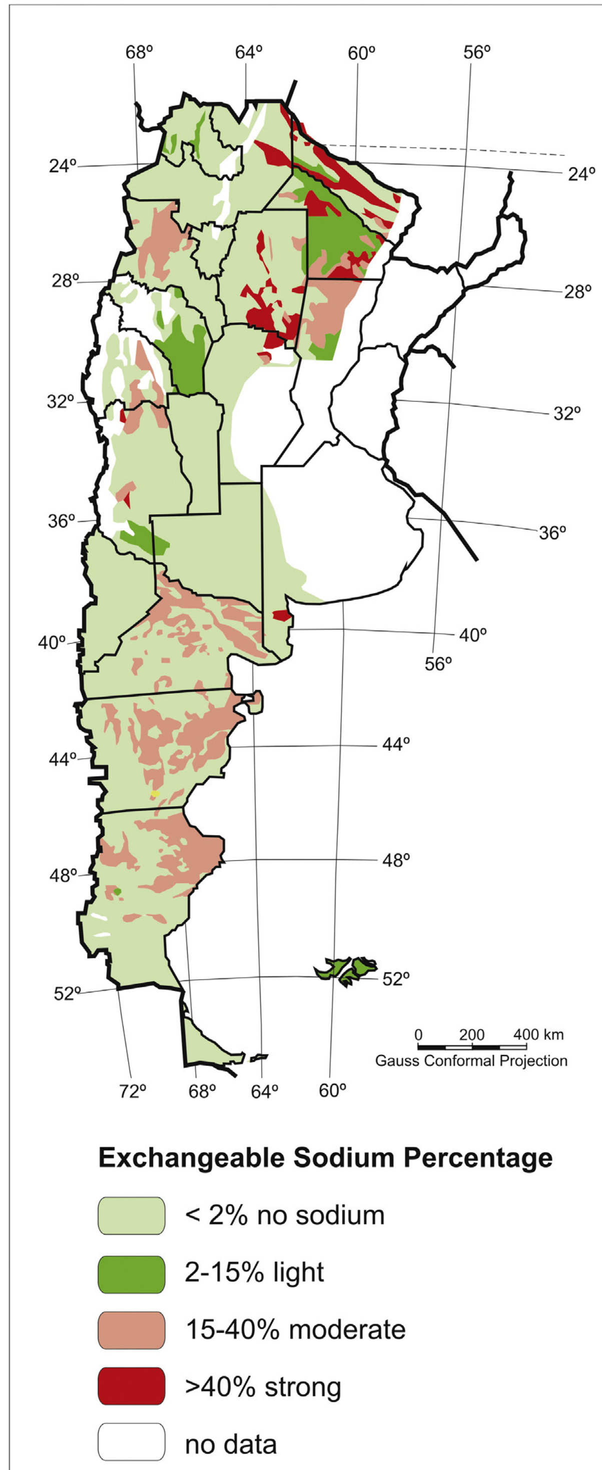

Fig. 7. Alkalinity of soils in Argentinean drylands (FAO, 2008) in dry regions (arid, semiarid and dry-subhumid climates, according to FAO (1996)).

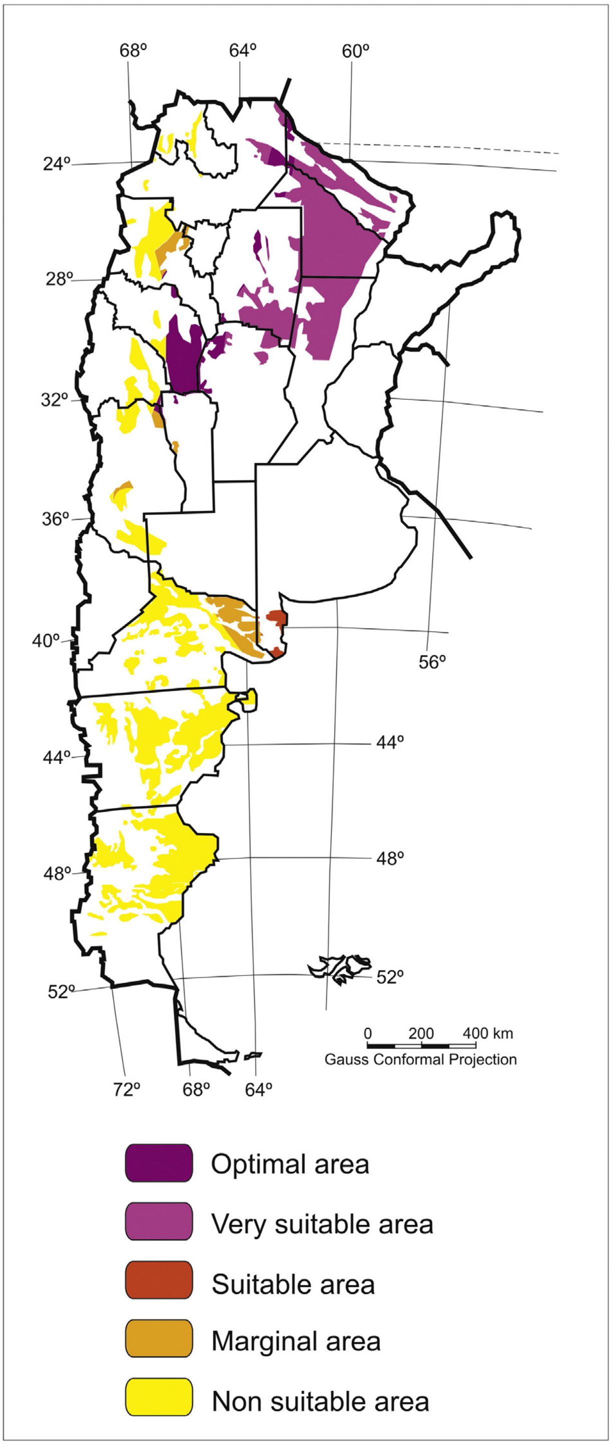

Fig. 8. Agro-ecological zoning for *Salvadora persica*.

shows the agro-ecological zoning for *S. persica* cultivation on halomorphic soils. The optimal area occupies the east and the south of the province of La Rioja. This is the most extensive area. There are also other small ones to the west of Cordoba, center of Santiago del Estero, east of Salta, west of Formosa and Chaco. A large part of Formosa, almost all Chaco, the north and center of Santa Fe, the south of Santiago del Estero and the north of Cordoba constitute very suitable areas. A suitable area can only be found in the south of Buenos Aires. Marginal areas are located in Rio Negro (in a region bordering La Pampa and Buenos Aires) and small areas in Mendoza and San Luis.

There is evidently a wide agroclimatic zone for the cultivation of *S. persica*. It spans from Northern Argentina to approximately 41° South latitude under dry-subhumid to semiarid climate conditions. This is in agreement with previous reports published by Duke (1983).

The expansion of alternative crops, and the subsequent amplification of the agricultural frontier affecting protected natural areas, could result not only in net increase of CO_2 emissions but also in a variety of negative consequences on biodiversity and the environment: loss of natural environments and landscape diversity, decreased quantity and quality of habitats, loss of flora and fauna diversity, diminished water, soil and air quality and similar negative events.

For this reason, the maps of the provincial and national protected areas (Fig. 9), the current land uses (Fig. 10) and the urban areas (Fig. 11), were superimposed on the Agro-ecological zoning (Fig. 8).

The overlap of these three maps on the agro-ecological zoning (Fig. 8) provided the "Potential cultivation zoning for *Salvadora persica*" (Fig. 12). In turn, this made it possible to estimate the land cover area for each agro-ecological zone based on the current land use.

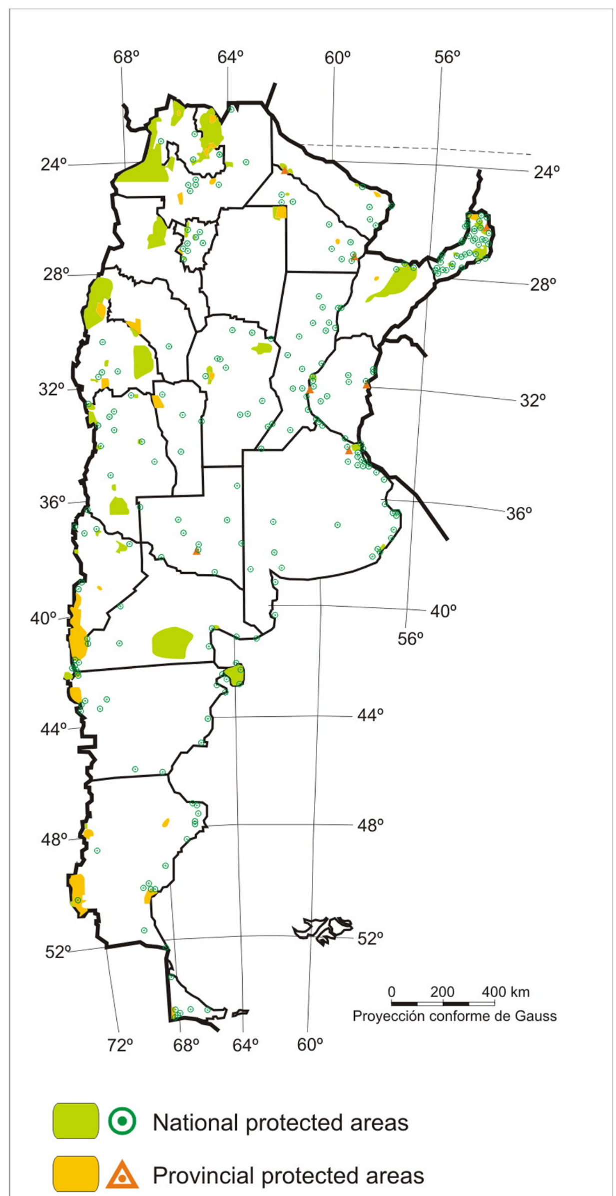

Fig. 9. Protected areas (Source: SAyDS).

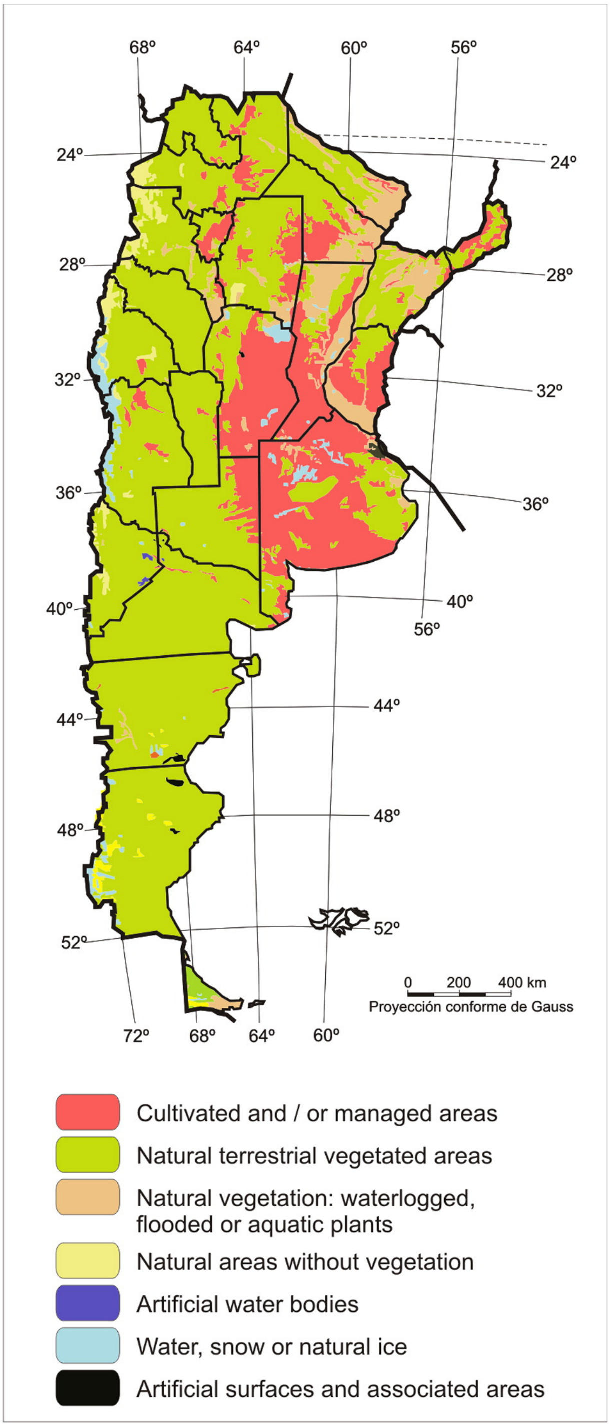

Fig. 10. Current land use and cover of the different zones (Source: INTA, 2009).

Fig. 12 shows the same 5 classes of suitability that Fig. 8, from optimal to non suitable areas, with decreasing levels of potential for agricultural development.

The spatial extent of the agro-ecological zones is given in Table 2. This table shows the real extent (in hectares) of each "Potential cultivation zone" (Agro-ecological zone), since the protected areas, urban areas and lands currently destined for other uses in Argentina were subtracted.

The optimal areas cover 4,311,055 ha and these are natural terrestrial vegetated areas. The lands classified as very suitable areas present natural terrestrial vegetation (5,734,400 ha) and natural vegetation waterlogged, flooded or aquatic plants (7,079,540 ha).

Both suitable areas (235,494 ha) and suitable areas with constraints (3,314,943 ha) are populated by natural terrestrial vegetation.

The potential cultivation zoning is useful for further analysis. Each potential cultivation zone has a similar combination of limitations and potentialities for land use.

A larger scale map can show more detail of actual current uses of the land and potentials for bioenergy (if this is indeed a key expected use in the future), and for defining pilot projects in Argentina to start growing *S. persica* in these areas. The cultivation of this species to obtain oil for biodiesel and other valuable products is possible in the areas classified as optimal, very suitable and suitable. In these regions, it would not be competing for farmable land and the winter frosts would not be lethal to the plant. Furthermore, the use of saline and alkaline lands is becoming increasingly important in a world that is permanently demanding more land for traditional food crops. Saline lands can be productive during drought periods and can be irrigated with low to very low quality groundwater, which is usually shunned by traditional farmers due to its high salt content.

The cultivation of halophytes as biofuel crops on marginal agricultural land would allay fears concerning the loss of land available for food production, but used instead for the biofuel industry (Qadir et al., 2008).

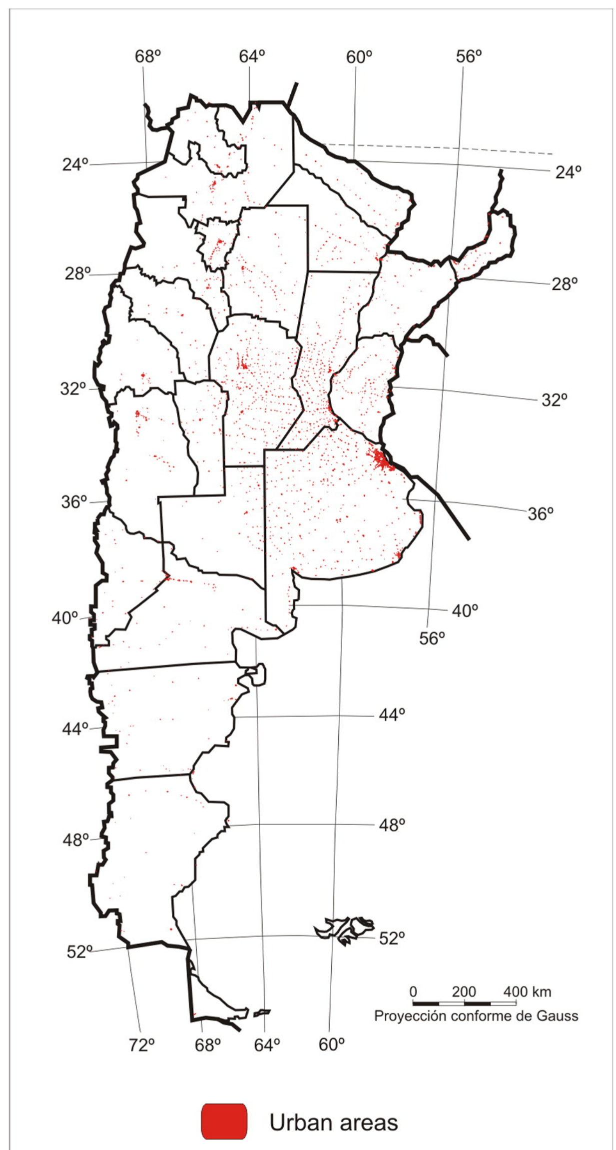

Fig. 11. Urban areas (Source: IGN, 2013).

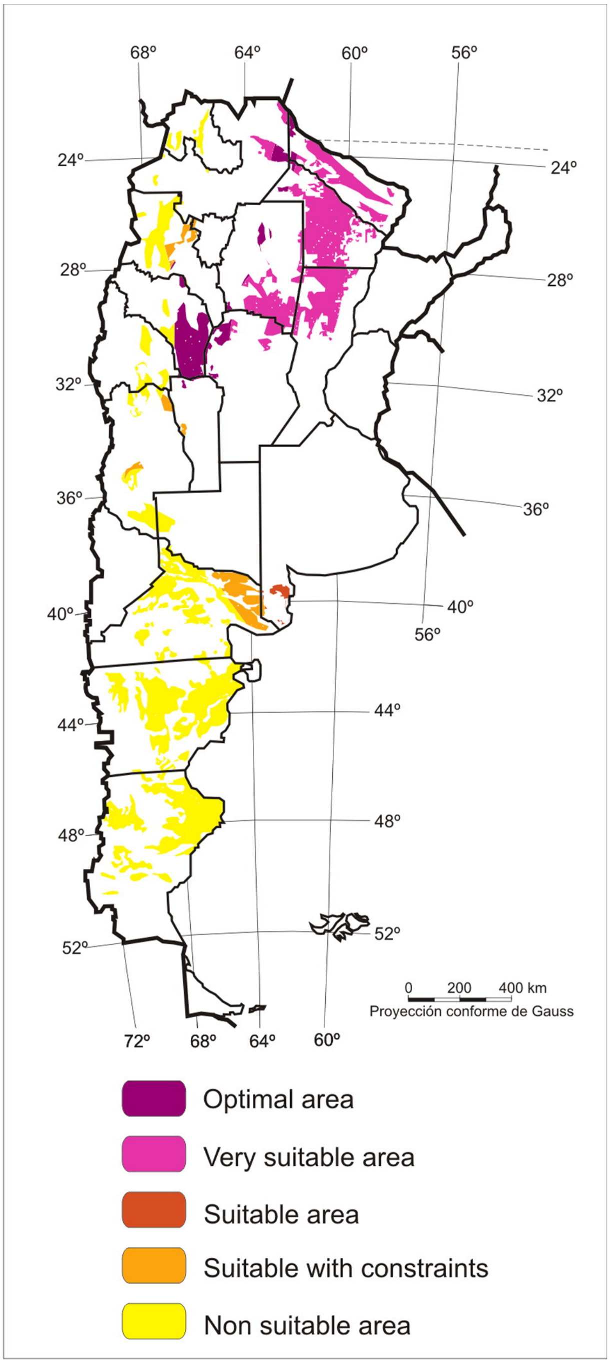

Fig. 12. Potential cultivation zoning for *Salvadora persica*.

This species also produces beneficial environmental effects as a result of its phytoremediation potential. Among these, promotion of soil-aggregate stability and creation of macropores that improve soil hydraulic properties can be highlighted. It also enhances the availability of plant nutrients in soil due to an increased exploration zone in terms of soil depth. Furthermore, its cultivation is environmentally friendly as concerns carbon sequestration in the post-amelioration soil (Qadir et al., 1996).

In addition, the cultivation of *siwack* in previously arable lands that were abandoned due to anthropogenic or natural salinization can contribute to the mitigation CO_2 emissions. The cultivation of *S. persica* will be useful not only to extract oils for biodiesel production, but also to obtain a variety of compounds with proven or potential applications, particularly as pharmaceuticals. This crop may generate new business

Table 2
Land area covered by each agro-ecological zone.

Potential cultivation zone	Current cover of the different zones	Land cover area (ha)
Optimal area	Natural terrestrial vegetated areas	4,311,055
Very suitable area	Natural terrestrial vegetated areas	5,734,400
	Natural vegetation waterlogged, flooded or aquatic plants	7,079,540
	Total very suitable areas	13,404,340
Suitable area	Natural terrestrial vegetated areas	235,494
Suitable area with constraints	Natural terrestrial vegetated areas	3,314,943
Total area of suitable lands		21,265,832
Non suitable areas on halomorphic soils	Natural terrestrial vegetated areas	29,225,045

opportunities in Argentine rural areas. Besides its direct use as crop, this halophyte will be useful for re-vegetation and remediation of salt-affected lands.

Therefore, this species, which can be called "cash crop halophyte" (that could even be irrigated with saline water), introduce a new concept of sustainable agriculture.

This paper represents a pioneering work since there are no previous studies concerning the introduction of *S. persica* in Argentina. In fact, the species is completely unknown in our country and not even our agronomists are aware of its existence and potential. Agro-ecological zoning for siwack will be an essential tool for agricultural planning.

4. Conclusions

The authors designed an agro-ecological zoning model based on international bibliography. This model can be used in any part of the world, employing the same agro-ecological indices presented in this paper.

It was established that there is an extensive agro-ecological zone for cultivation of *S. persica* that extends from Northern Argentina to approximately 41° South latitude, under dry-subhumid to semiarid climates on halomorphic soils. Lands classified with different degrees of suitability at the potential cultivation zoning could be used for production of this species for energy purposes, inasmuch as those lands are not assigned for food production (whether traditional crops or cultivated pastures), or urban or protected areas.

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