Agroclimatic zoning for *Lesquerella fendleri*, a multipurpose oilseed crop for production in Argentina

Silvia Falasca[1], Sandra Pitta-Alvarez[2,3] and Carolina Miranda del Fresno[4]*

Abstract: *Lesquerella produces a small seed that has 25 to 30% oil, containing 55 to 64% hydroxy fatty acid. The oil is useful for industrial applications, cosmetics, pharmaceuticals and biodiesel. Lesquerella is valued for both its oil and gum. The gum can be used as a thickener in various industrial and food products. The aim of this paper was to develop an agro-climatic zoning model to determine the potential growing areas for* Lesquerella fendleri *in Argentina. To define the agroclimatic suitability of this crop, the climatic data of the meteorological stations corresponding to the period 1981-2010 were analyzed. The moisture factor, in particular the average annual isohyets of 250, 400 and 1100 mm, was first examined. Annual rainfalls lower than 250 mm determined a non-suitable area, from 250-400 mm the area was deemed suitable, optimal from 400–1100 mm and >1100 mm included another suitable area. The thermal factor was also considered, and annual temperatures < 13ºC determined a non-suitable area. For the growing period, different ranges of temperatures were contemplated: temperatures below 8ºC defined a non-suitable area; from 8 to 11ºC a suitable one; while between 11 and 18ºC the area was optimal and temperatures greater than 18ºC defined another suitable area. Finally, it was determined that the intensity of the winter frosts should be less than -10ºC, so as not to have a lethal impact on Lesquerella. Based on international bibliography, the authors outlined an agro-climatic zoning model for* L. fendleri*, where 7 classes of suitability were differentiated. This work was performed by the implementation of a Geographic Information System. The GIS database can be updated easily in the future with new data or with better spatial resolution data. If the purpose of the crop is to obtain pharmaceutical compounds, cultivation in optimal, very suitable, suitable and suitable with irrigation would be recommendable. Instead, if the oil is to be destined for biodiesel production, it is convenient to relocate cultivation to areas classified as suitable under subhumid and semiarid regime. Growing this cash crop in semi-desert regions would ensure lack of competition with lands destined for traditional crops.*
Keywords: Lesquerella fendleri, *bioclimatic requirements, agroclimatic zoning, subhumid to semiarid climate, Argentina.*

Riassunto: *Lesquerella produce un piccolo seme con un contenuto di olio variabile da 25 a 30% di cui il 55-64% di acido grasso idrossilato. L'olio è utilizzato per applicazioni industriali, cosmetiche, in prodotti farmaceutici e per la produzione di biodiesel. Lesquerella è apprezzata sia per il suo olio che per la sua gomma. che viene principalmente utilizzata come addensante in vari prodotti industriali e alimentari. L'obiettivo di questo lavoro è stato quello di sviluppare un modello di zonazione agro-climatica per la determinazione di potenziali aree di crescita per* Lesquerella *in Argentina. Per definire l'idoneità agroclimatica di questa coltura in Argentina sono stati analizzati i dati climatici delle stazioni meteorologiche per il periodo 1981-2010. La disponibilità idrica è stata inizialmente considerata, in particolare, individuando isolinee con medie annuali di 250, 400 e 1100 mm. Le precipitazioni annuali inferiori a 250 mm hanno determinato un'area non idonea, da 250 a 400 mm l'area è stata ritenuta idonea, ottimale da 400-1100 mm e > 1100 mm idonea. È stato anche considerato il fattore termico e le temperature annuali <13ºC hanno determinato un'area non adatta. Per il periodo di crescita sono state previste diverse gamme di temperature: le temperature al di sotto degli 8 °C hanno definito un'area non adatta; da 8 a 11 ºC condizioni adeguate; mentre tra 11 e 18 °C l'area è ottimale. Le temperature superiori a 18 ° C hanno definito un'altra area adeguata. Infine, è stato determinato che i valori minimi invernali dovrebbero essere non inferiori a -10 °C, in modo da non avere un impatto letale su Lesquerella. Sulla base della bibliografia internazionale, gli autori hanno delineato un modello di zonazione agro-climatica in Argentina per* Lesquerella fendleri *dove sono stati differenziate 7 classi di idoneità. Se lo scopo della coltura è quello di ottenere composti farmaceutici, sarebbe raccomandabile una coltivazione in area ottimale, molto idonea, idonea e idonea all'irrigazione. Invece, se l'olio deve essere destinato alla produzione di biodiesel, è conveniente ricollocare la coltivazione in aree classificate come idonee sotto regime subumidico e semiarido. Coltivare questo specie in regioni semi-desertiche garantirebbe la mancanza di concorrenza con le terre destinate alle colture tradizionali. Questo lavoro è stato fatto mediante l'applicazione di un Sistema Informativo Geografico, il cui database può essere facilmente aggiornato con nuovi dati a maggiori livelli di risoluzione.*
Parole chiave: Lesquerella flenderi, *requisiti bioclimatici, zonazione agroclimatica, clima subumido e semiarido, Argentina.*

* Corresponding author's e-mail: sfalasca@conicet.gov.ar; slfalasca@gmail.com
[1] CONICET. INTA. Climate and Water Institute. Las Cabañas y Los Reseros S/N. Castelar. Buenos Aires, Argentina.
[2] Laboratorio de Cultivo Experimental de Plantas y Microalgas, Departamento de Biodiversidady Biología Experimental, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Argentina.
[3] Instituto de Micología y Botánica (INMIBO), Universidad de Buenos Aires-CONICET, Ciudad Autónoma de Buenos Aires, Argentina.
[4] University of the Center of Province of Buenos Aires. School of Humanities, Environmental Studies and Research Centre. CINEA. Pinto 399. Tandil, Buenos Aires, Argentina..
Submitted 11 May 2016, accepted 15 January 2018

DOI:10.19199/2018.1.2038-5625.005

1. INTRODUCTION

World energy demands have grown dramatically due to unprecedented economic growth. To sustain this expansion, countries need safe, easily available and affordable sources of energy.

One of the best alternatives is producing biofuels from local sources. Biodiesel, for instance, is renewable and environmentally friendly. Its properties are similar to petro-diesel, but its carbon dioxide (CO_2), sulfur and particulate emissions are dramatically lower. The potential of vegetable oils for the manufacture of biofuels is immense, since they are renewable and environmentally beneficial. When considering oilseed crops for biodiesel production, each country should examine a series of factors, such as geography, climate and economics.

In the first place, plant development and crop production are affected by climate conditions. Several factors condition the growing period, such as distribution of solar radiation, rainfall regimes, range of temperatures and day length. Prior to the introduction of a new species in a country, knowledge of its bioclimatic requirements is mandatory. Agroclimatic zoning is crucial for successful crop expansion because it allows identification of areas with agroclimatic suitability.

Plants need a minimum as well as a maximum offer from the climate to satisfy their physiological needs; beyond such limits they are negatively affected. The range between these two values represents the energetic level that plants need for their physiological complex to work efficiently. This range is called "ideal temperature" (Ometo, 1981).

There is growing interest worldwide in *Lesquerella* genus due to novel properties absent in other oilseeds. Currently, there are several research efforts to introduce it successfully into agriculture.

L. fendleri (A.Gray) S.Wats. belongs the Brassicaceae (mustard) family. It has different common names, such as bladder-pod, desert mustard, popweed, yellow-top, fendlers bladderpod or lesquerella. It is native to the plains and tablelands of southwestern United States, eastward to Kansas, Texas to central Arizona and southward from central Colorado into northern Mexico (Duke, 1983; Dierig, 1995).

Although *L. fendleri* is a perennial species, it is commonly grown in production as an annual because seed-yield tends to reduce perennially (Dierig *et al*, 1993; Brown and Arquette, 1994; Dierig, 1995; Dierig *et al.*, 1996). Plants geminate in late summer – early autumn, and exhibit little vegetative growth during winter. However, by late spring, growth, flowering and seed set increase. At seed maturation or in low moisture conditions, the plant dries and the taproot breaks off. The resulting dried plant blows about like tumbleweeds, dispersing the seeds (Duke, 1983).

A relatively new crop, bladder-pod has no recognized cvs. Because it is very polymorphic, "certainly the most polymorphic in the genus", it offers genetic material for selection and breeding (Duke, 1983).

1.1 Bladder-pod: potential uses

Plants from various species of the genus Lesquerella have been mentioned as prime candidates for new crops development because they are a source of hydroxy fatty acids (HFA) (Thompson and Dierig, 1988; Thompson, 1988). Annual (*Lesquerella fendleri, L. gracilis* and *L. angustifolia*) and perennial (*L. mendocina* and *L. pinetorum*) have been selected for introduction and domestication programs in arid lands due both to their agronomic potential and their tolerance to drought. However, *Lesquerella fendleri* has the most promise for domestication in arid parts of the world because of its superior productivity and amenability to farm management practices (Dierig *et al.*, 1993).

Lesquerella produces a small seed that contains 25 to 30% oil. This oil is composed of 55 to 64% hydroxyl fatty acids, which are 55 to 60% lesquerolic (C20:1OH 14-hydroxy-eicosa-cis-11-enoic acid (Smith *et al.*, 1961) and auricolic (2-4%, 14-hydroxy-cis-11-cis-17-eicosenoic acid) (USDA, 1991). These molecules, known as estolides, are what make this oil unique and allow it to flow more easily than petroleum at cold temperatures.

According to Goodrum and Geller (2005), the oil used in engine oil at concentrations as low as 0.25%, performs better than castor, soybean, and rapeseed methyl esters in diminishing wear and damage in fuel injected diesel engines.

Lesquerolic acid is similar to ricinoleic acid and the only difference between the two is that lesquerolic acid has two additional methylene groups on the carboxyl end of the molecule. This suggests that lesquerella oil and its derivatives may be a competitive alternative to castor oil. However, castor oil contains approximately 90% of the desired HFA, while lesquerolic acid constitutes only 50% of lesquerella oil. This requires more extensive purification methods and careful identification of the adequate component. In addition, Lesquerella contains α-hydroxy phosphonates and their corresponding phosphonic acids. These display a large variety of biological activities, as enzyme inhibitors, pesticides, antibiotics and anti-cancer therapeutics (Cusimano *et al.*, 2014).

In terms of biodiesel standards, the methyl esters of Lesquerella oil have a higher cetane number (45. 6 vs. 37.55) and lower kinematic viscosity (11.22 vs. 14.82 mm^2/s) than those of castor oil (*Ricinus communis*).

Both values for Lesquerella methyl esters are closer to specifications in biodiesel standards, while oxidative stability of castor methyl esters is apparently higher. In general, Lesquerella methyl esters appear to have more favorable fuel properties than castor methyl esters although sulfur content is elevated. Both types of methyl esters have a greater tendency to exceed free glycerol and water specifications in biodiesel standards (Knothe *et al*, 2012).

According to Sanford *et al.*, (2009), the analysis of biodiesel show: cloud point: -11.6, CFPP: -6, acid number: 0.630; oxidative stability (110 °C): 10.5; flashpoint (closed cup) > 160). Currently, Lesquerella oil products as biodiesel additives are being evaluated (Goodrum and Geller, 2005; USDA, 2008).

Furthermore, the seed also contains 20-25% of protein, and it can be employed as supplement for livestock (Duke, 1983). The seed also has a unique natural gum, which can be separated before or after extracting the oil. As a result, Lesquerella is valuable for both its oil and gum. The gum could be used as a thickener in various industrial and food products.

The oil can also be used to manufacture cosmetic products such as lipsticks and sunscreens (Compton *et al.*, 2004) due to its low toxicity and ocular, dermal and anal irritation levels. It can also be employed to manufacture a plastic tougher than those currently available. Other uses include adhesives, lubricants, pharmaceutical products, waxes, varnishes, soaps, detergents, greases, motor oils, dyes and sealants (Muuse *et al.*, 1992; Dierig *et al.*, 1993; Adamsen *et al.*, 2003).

High concentrations of cinnamoyl esters, which are used in sunscreens, have been reported in *L. fendleri* (Compton *et al.*, 2004). Furthermore, epoxy compounds and low levels of very long chain fatty acids have also been detected.

1.2 Productivity

According to Roseberg, (1996) yields stand between 950 and 1,120 kg ha^{-1}, while in advanced lines yields of up to 1,800 kg ha^{-1} have been observed. In small experimental plots and under dry conditions, yields average about 1,600 kg ha^{-1}. Considering that oil percentage is about 30% (11-39%), oil yields of as high as 1 MT/ha seem unlikely without more germplasm and selection (Buchanan and Duke, 1981).

Grieve *et al*, (1997) showed that, at the highest salinity level (10.5 dS m^{-1}), seed yield decreased from 2100 kg ha^{-1} (non-saline control conditions) to 650 kg ha^{-1}. They found that for each unit increase in soil salinity above a threshold of 6.1 dS m^{-1}, there was a 19% reduction in seed yield. The same authors reported that seed total oil content increased slightly, albeit significantly, as salinity increased. Oil composition did not change with salinity level, except for a small but also significant increase in linolenic acid (C18:3).

The species *Lesquerella mendocina* (synonym: *Alyssum mendocinum, Lesquerella aff. Mendocina, L. montevidensis, Vesicaria artica, Vesicaria mendocina, Vesicaria montevidensis)* is native to Argentine Patagonia (Ploschuk *et al.*, 2003) and it probably has the same uses as *L. fendleri*. It is a perennial herbaceous species, with erect stems and abundant pubescent leaves that reaches heights of up to 50 cm and develops terminal clusters with yellow flowers. The fruits are hemispherical, with a diameter of 5-11 mm. The species has been detected in the following provinces: Buenos Aires, Chubut, Córdoba, Jujuy, La Pampa, La Rioja, Mendoza, Neuquén, Río Negro, Salta, San Juan, San Luis and Tucumán (SIB, N/D). However, there are no commercial plantations in Argentina.

According to Ploschuk *et al.*, (2003) in assays carried out in Rio Chubut Valley, Patagonia, Argentina with *L. angustifolia*, 725 kg ha^{-1} of seeds were obtained, with an oil content of 22%, while *L. fendleri* yielded only 174 kg ha^{-1}, and the oil content was 19.8%.

In this investigation, the aim was to determine potential growing areas for *Lesquerella fendleri* in Argentina by developing an agro-climatic zoning model.

2. MATERIALS AND METHODS

2.1 Study area

The area studied was the Argentine Republic, which 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.

Argentina is characterized by its vast territory and outstanding climatic diversity. The climatic traits of the different regions are influenced by numerous geographic factors. In particular, the Argentine Republic features great latitudinal development: 21º46′ in the North to 55°03′S in Cape San Pío, in the South. The extreme eastern limit of the country is located at 53°38′W, in the town of Bernardo de Irigoyen (Misiones province).

2.2 Ecological requirements

According to FAO-Ecocrop, (2007) the life zone of this species extends from steppe semiarid (Bs), to temperate oceanic (Do) and temperate continental climate (Dc). In its native form, it grows at altitudes between 600 and 1800 m above sea level. However, according to Dierig et al, (2006) *L. fendleri* is suitable for production in areas below 700 m. It develops in regions with annual precipitations between 250 and 400 mm (Duke, 1983;

Thompson, 1988; Thompson and Dierig, 1988; Dierig and Thompson, 1993). However, Duke (1978) and FAO-Ecocrop (2007) reported that growth demanded an annual rainfall range of 250-1500 mm with the optimum between 300-1100 mm. It flourishes in areas with 250-400 mm rainfall from September through April (North Hemisphere), sharing a similarity to the requirements of winter grains. The plant responds well to irrigation.

Although the optimum temperature range during the growing period is 11-18°C, *L. fendleri* can tolerate a range of 8-25°C (FAO-Ecocrop, 2007). According to Duke (1978) it can tolerate annual temperatures of 13 to 15°C. The crop is cold tolerant and in the natural adaptation sites of the North Hemisphere, where temperatures of -6 a 0ºC are common during January, it can endure -10ºC in winter (Duke, 1983; Roseberg, 1996), suggesting its use for high latitudes cultivation.

Lopez *et al,* (2004) determined a base temperature of 5ºC to calculate the thermal summation needed to reach each phenological stage in the center of Chile. Research carried out in Argentina, pertaining to the influence of temperature in the extent of the emergency-flowering phase, indicated that temperature is the most important factor in determining the length of that period and, consequently, the cultivation cycle (Windauer and Ravetta, 1997). Windauer *et al* (2004) found that the rate of development of *L. fendleri* increased linearly with temperature in the phase from emergence to floral bud appearance over the range 9º to 20ºC and for the phase from floral bud appearance to first flower open over the range 9º to 24ºC. Windauer *et al* (2006) concluded that, for *Lesquerella* species, the optimal temperature from emergence to floral bud appearance is 20ºC.

Ploschuk *et al.,* (2003) carried out assays with spring and autumn sowings in the Chubut River Valley, Patagonia (Argentina) and determined that yields of *L. fendleri, L. angustifolia and L. gordonii* were reduced by 80% in spring sowings in comparison to autumn ones. The authors attributed this difference to the day length and the high summer temperatures in these latitudes, since there was flower induction in plants with scarce biomass.

Flowering lasts approximately 12 weeks, but the first 4 to 6 weeks of flowering are the ones that most influence yields. Bees are necessary both to pollinate and to ensure high yields (Adamsen *et al.*, 2003). The flowering period and the initiation of grain filling are two phenological stages highly sensitive to hydric stress (Hunsaker *et al.*, 1998). Absence of water delays flowering up to 15 days and reduces the production of stems per plant (Ploschuk *et al,* 2001).

The seeds present an annual dormancy/non-dormancy cycle, and this depends on the storage conditions. For germination, the temperature range is 5 to 35ºC, with 20 to 28ºC being optimal (Adam *et al.,* 2007). According to Hyatt *et al.*, (2001) in addition to the appropriate temperature, the seed also requires light exposure.

The plant has been reported to tolerate high pH (Duke, 1978), since it can exclude sodium when it reaches toxic levels (Grieve *et al.*, 1998). This allows the species to adapt to high salinity soils (Foster, 1999). Salt tolerance of established *Lesquerella* is 6.9 dS m^{-1}, which is interpreted as "moderately tolerant" (Grieve *et al.,* 1997). Furthermore, it absorbs high concentrations of selenium in saline conditions, making it a candidate for phyto-remediation of soils (Grieve *et al.*, 2001).

According to Roseberg, (1996), probable production areas could include Southeast and Center-South USA, Western Australia, North of Argentina, Center South of Chile and North Africa.

2.3 The agro-climatic zoning

Agro-climatic zoning allows the identification of regions with different potential yields, according to their environmental conditions. To develop this properly, the requirements, limits and bio-meteorological tolerance and conditions for this species were taken into account. Furthermore, the climatological characteristics of native areas and the regions of successful cultivation around the world were also considered.

To establish the agro-climatic aptitude of this crop in Argentina, the climatic data collected in the period 1981-2010 from all the meteorological stations were analyzed. To classify suitability classes, thermal and hydric limits were defined, based on the bibliography cited above. The focus first turned to the moisture factor, and the average annual isohyets of 250, 400 and 1100 mm were analyzed. Annual rainfalls lower than 250 mm determined a non-suitable area, from 250-400 mm the area was deemed suitable (Duke, 1983; Dierig and Thompson, 1993), optimal from 400-1100 mm (FAO-Ecocrop, 2007) and >1100 mm included another suitable area.

The thermal factor was then considered, and annual temperatures < 13ºC determined a non-suitable area and > 13ºC a suitable one (Duke, 1978). For the growing period, different ranges of temperatures were contemplated. Temperatures below 8ºC defined a non-suitable area; from 8 to 11ºC a suitable one; while between 11 and 18ºC (FAO-Ecocrop, 2007) the area was optimal and temperatures greater than 18ºC defined another suitable area. Finally, it was determined that the intensity of the winter frosts should be less than -10ºC (Duke, 1983; Roseberg, 1996), so as not to have a lethal impact on Lesquerella.

Through the use of a Geographic Information System

(GIS), the processes were automated according to procedures involving data capture, storage, analysis, updating, information management, publication and query. In all GIS analysis, several tools are employed: spatial statistics techniques, information technology and geographic and statistic databases. To obtain the maps, a series of previously interpolated bioclimatic variables were used, and these were processed with the 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 GIS Program, following the Ordinary Kriging interpolation method. The agro-climatic zone map was obtained by overlaying the previous maps.
To construct the classified areas with different grades of agro-climatic suitability, Argentina's political map, with the toponymy of the provinces was included (Fig. 1).

3. RESULTS

The delimitation of moisture regions can be observed in Fig. 2. The mean annual isohyets of 250, 400 and 1100 mm were included. The region studied is characterized by 4 areas with distinct precipitation regimes: <250 mm represents a non-suitable area, 250-400 mm a suitable one, from 400-1100 mm the area is optimal and >1100 mm determines another suitable area. From a hydric point of view, it is clear from the figure that non-

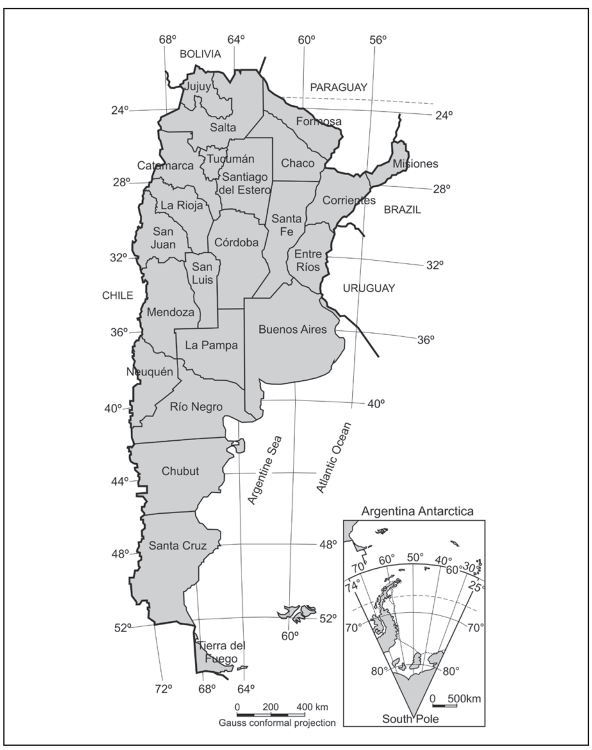

Fig. 1 - Argentina´s political map.
Fig. 1 - Mappa politica della Argentina.

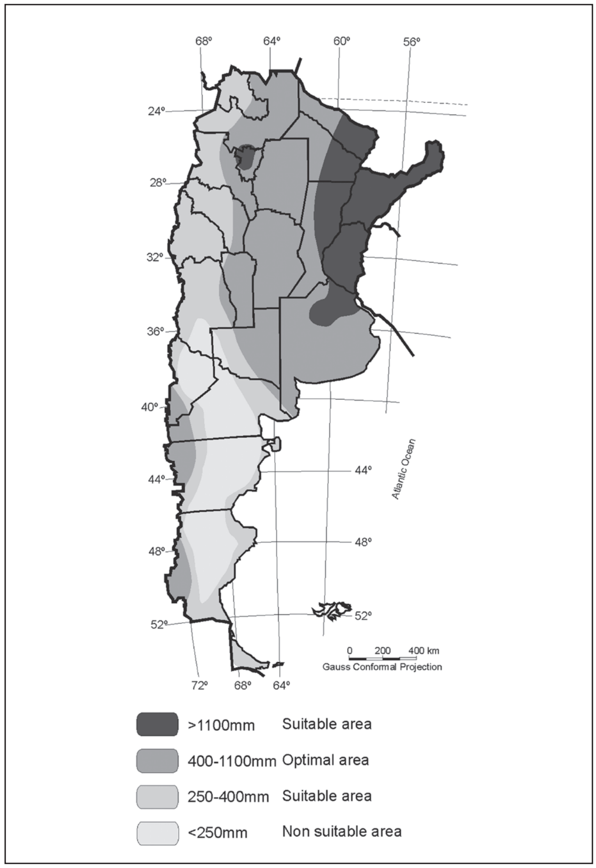

Fig. 2 - Moisture regime: Annual rainfall.
Fig. 2 - Regime idrico: Precipitazioni annuali.

suitable lands occupy less territory than suitable lands. The main Pacific semi-permanent anticyclone flow to the west is separated from the Atlantic semi-permanent anticyclone, to the east of Argentina, by the Andes Mountains. The singularities associated with predominant topographical and atmospheric conditions determine regional precipitation. To the North of the Colorado River, rainfall decreases from east to west. The first rainfall maximum is usually during autumn. In addition, there is a prevailing circulation derived from the semi-permanent Atlantic anticyclone and air masses that originate in tropical areas.
The climate of the majority of South America's west coast is affected by the eastern part of the South Pacific anticyclone, which causes stable and dwindling air conditions that result in minimal precipitation. Windward of the Andes, southern 35°S, the region exhibits a winter precipitation regime and snowfalls represent more frequent precipitations. As the westerlies rise over the Andes, most of their moisture is released in orographic precipitation (Patagonian-Fuegian Andes with > 1000 mm) while on the leeward side a typical rain shadow develops over the

Agroclimatic suitability class	Annual rainfall (mm)	Mean annual Temperature (°C)	Growing period temperature (°C)	Minimal annual temperature (°C)
Optimal area	400-1100	> 13	11-18	>-10
Very suitable area (semiarid regime)	250-400	> 13	11-18	>-10
Suitable area (humid regime)	> 1100	> 13	11-18	>-10
Suitable area (subhumid regime)	400-1100	> 13	18-25	>-10
Suitable area (semiarid regime)	250-400	> 13	18-25	>-10
Suitable area with Irrigation (arid regime)	< 250	> 13	18-25	>-10
Non suitable area	< 250	< 13	< 11	>-10

Tab. 1 - Classes of agroclimatic suitability and limits for each class.
Tab. 1 - Classi di attitudine agroclimatica e limiti di ogni clase.

vast desert and semi-desert region of Patagonia. The winds emanating from the South Atlantic anticyclone produce greater amounts of precipitation on the east coast of Patagonia, and the humidifying action of the warm air currents forms a belt of low pressure.
In Fig. 3 thermal regions were considered. Argentina has a mild climate, with warm summers that last from late December through late March. Winters are benign and last from late June to September. Northern regions have the highest temperature, while the lowest ones

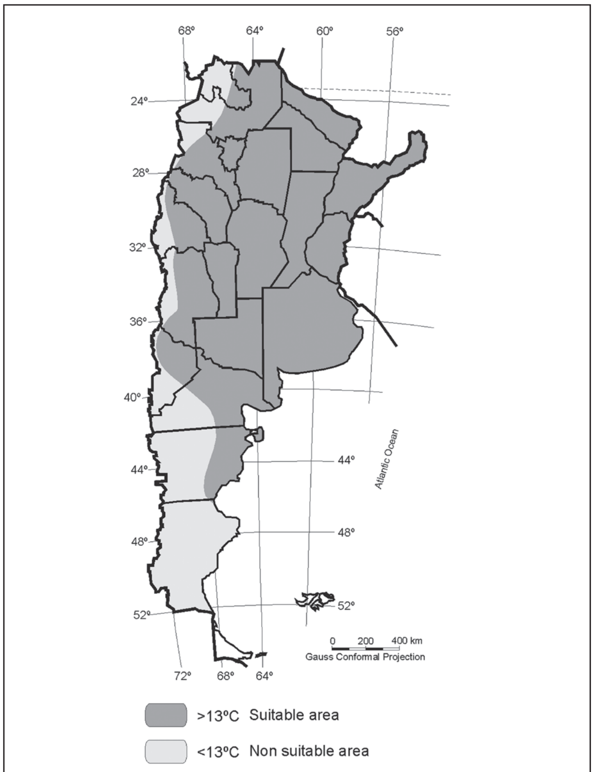

Fig. 3 - Thermal regime: Mean annual temperature > 13°C.
Fig. 3 - Regime termico: Temperatura media annua > 13°C.

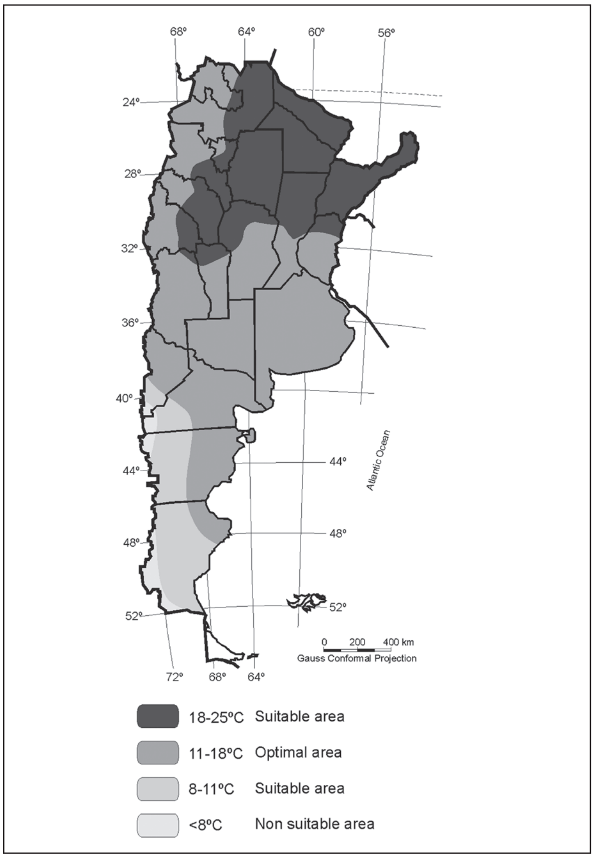

Fig. 4 - *Lesquerella* growing period temperature.
Fig. 4 - Lesquerella: temperatura nel periodo di crescita.

can be found in the South. Consequently, the isotherm correlated to the average annual temperature of 13°C establishes non-suitable areas to the south and to the west. Non-suitable areas for *Lequerella* cover the west of Argentina and the center-west of Patagonia region. Fig. 4 shows the mean temperature of growing period. Average temperatures range from 25°C in the north of

Argentina to 8ºC in Tierra del Fuego. Distribution of isotherm of 18ºC shows that a South-North gradient prevails affected only by the latitude factor in plain areas. However, it diverts from its path to the South due to the altitude factor generated by the saws of Córdoba and San Luis, and the Sierras Pampeanas. Afterwards, it deflects to the North by the Andes Mountain effect. The trail followed by the 11ºC isotherm shows a pronounced oceanity effect. This figure shows that, in Argentina, non-suitable areas are reduced due to the favorable temperatures of growing period.
Fig. 5 shows the minimum lethal temperature for this species, which is -10°C. These low temperatures recur once every 30 years. Non-suitable areas cover the west of the country, the west and center of Patagonia and the Argentinean saws areas.
By superimposing the four maps (Fig. 2, 3, 4 and 5), the Agro-climatic zoning seen in Fig. 6 was drawn, and seven suitability classes were determined. The **Optimal area** covers almost all the province of Buenos Aires, east and center of La Pampa, south and center of the provinces of Santa Fe, Cordoba and San Luis, east of Mendoza and northeast of Rio Negro. To the west, a **very suitable area** can be detected in the form of a strip that covers part of the provinces of San Juan,

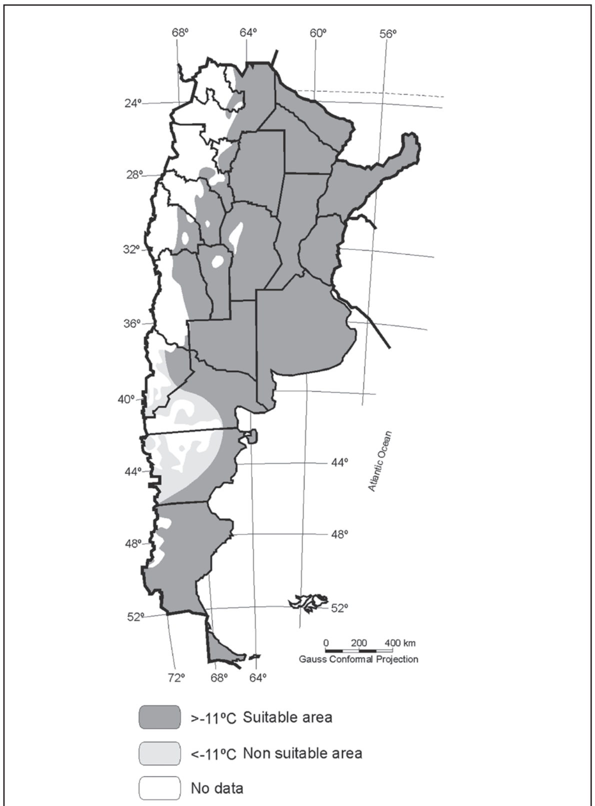

Fig. 5 - Absolute minimum temperature > -10ºC.
Fig. 5 - Temperatura minima assoluta > -10ºC.

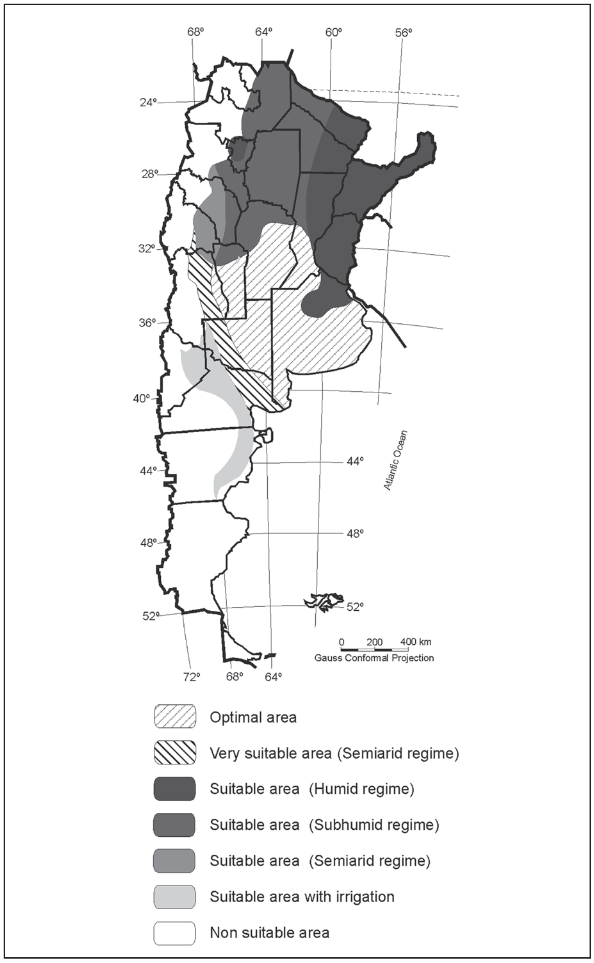

Fig. 6 - Agroclimatic suitability for the cultivation of *Lesquerella spp.*
Fig. 6 - Attitudine agroclimatica per la coltivazione di Lesquerella spp.

Mendoza, La Pampa and Rio Negro. Towards the west, a **suitable area with irrigation** can be found, and it comprises east of Neuquén, west of La Pampa, and part of the provinces of Rio Negro and Chubut. A **Suitable area under semiarid regime** covers part of San Juan, La Rioja and Catamarca, NE of Mendoza and NW of San Luis provinces. However, a **suitable area under humid regime** covers the Mesopotamian Region (Misiones, Corrientes and Entre Ríos), north of Buenos Aires and the oriental sector of Chaco, Formosa and Santa Fe. The same situation can be observed in the province of Tucuman in the Northwest of the country.
The **suitable area under subhumid regime** comprises the north and the center of Argentina, and its southern limit is the north of Córdoba and San Luis and the center of Santa Fe province.
Finally, **non-suitable areas** present two or more of the constraints listed in Tab. 1.

4. DISCUSSION

According to FAO-Ecocrop (2007) *Lesquerella* grows on a variety of soil types. It thrives on calcareous soils (better on sandy loams). It is a pioneer crop on disturbed soils, which are dry, open, well-drained sites. The reported soil pH range for growth is 5.6-8.3, with the optimum between 6.5-8.

If the purpose of cultivation is to obtain pharmaceutical compounds, oil yield should be optimized. Therefore, cultivation in the following areas are recommendable: optimal (where Molisols soils predominate), very suitable (Aridisols and Entisols soils), suitable with humid regime (Molisols, Ultisols, Vertisols, Histosols and Alfisols soils) and suitable with irrigation (Aridisols and Entisols Order). Argentina imports castor oil, but it could be substituted by extensive cultivation of Lesquerella, which would yield a low-price commodity for the chemical industry.

Instead, if the oil is to be destined for biodiesel production, it is convenient to relocate cultivation to areas classified as suitable under subhumid (Molisols and Alfisols order) and semiarid regimes (Entisols soils). Growing this cash crop in semi-desert regions would ensure lack of competition with lands destined for traditional crops.

Since the natural geographic distribution of *Lesquerella* is in arid regions, it is has probably adapted to resist drought, salinity stress and other environmental conditions. Therefore, other areas in the world with current, or future, salinity or sodicity problems are strong candidates for its extended agronomic development.

Unfortunately, since there are no *Lesquerella fendleri* commercial plantations in Argentina, the potential growing areas delimited by agroclimatic zoning in this paper cannot be corroborated. Only some preliminary assays have been carried out in semiarid climate in the Patagonia. Assuming that requirements for *L. fendleri* are similar to those of *L. mendocina,* the aim was to correlate the agroclimatic zones with the regions where this native species was recognized in our country.

L. mendocina, is widely distributed in highland regions and mountainous regions, from west of the province of Buenos Aires to Mendoza, and from North Patagonia to Jujuy (Correa, 1984). During the winter, in natural populations it remains as a rosette (vegetative state) and flowers between the end of August and the beginning of September, while the become seeds in early November.

L. mendocina (according to documented citations in the Argentine Biodiversity Information System / ND) has been recognized in the provinces of Buenos Aires, Chubut, Córdoba, Jujuy, La Pampa, La Rioja, Mendoza, Neuquén, Rio Negro, Salta, San Juan, San Luis and Tucumán. According to Discover Life (N/D) this species has been detected in the provinces of: Salta (25ºS and 64.5º W), Córdoba (32ºS and 64ºW), Mendoza (33.61ºS and 69.57ºW), Neuquén (39ºS and 70ºW), San Juan (31ºS and 69ºW), San Luis (34ºS and 66ºW) and Catamarca (27ºS and 67ºW). Furthermore, many authors reported the species in different protected areas of the country: Los Cardones (Salta), Quebrada del Condorito (Córdoba), Laguna Blanca (Neuquén) y Lihuel Calel (La Pampa) (Cabido and Acosta, 1986; Cabido and Acosta, 1985; Cabido, 1985; Novara, 2003; Zuloaga and Morrone, 1996; Mazzola *et al,* 2008).

In provinces of Santa Fe, Misiones, Entre Ríos, Corrientes, Chaco, Formosa and Santiago del Estero *L. mendocina* has not been observed. However, Fig. 6 shows agroclimatic suitability for *L. fendleri*. These regions have been classified as suitable areas, under humid regime, subhumid regime and semiarid regime. Ploschuk *et al,* (2001) compared the efficiency of water-use of *L. fendleri* with *L. mendocina,* and found that in *L. mendocina* it was 35% higher in sites with serious water limitations. Ploschuk *et al,* (2003) demonstrated that *L. angustifolia* behaves better than *L. fendleri* in the irrigated valleys of Patagonia; also, that yields for *L. fendleri* would be low in regions with extremely cold winters and high latitudes. Alvarez Prado and Ploschuk (2008) suggest that, for colder sites, *L. mendocina* might be an auspicious alternative to *L. fendleri.*

This could suggest that maybe *L. fendleri* could tolerate more abundant moisture regimes and higher temperatures than *L. mendocina* and, thus, could also produce acceptable yields in subhumid to humid regimes, situated in the eastern sector of Argentina.

The comparison of two related species of the same genus differing in life cycle clearly suggests that some traits of perennials have the potential to be introduced in breeding programs for new oil-seed crops for arid lands.

5. CONCLUSIONS

The authors, based on international bibliography, delineated an agro-climatic zoning model to determine potential production areas in Argentina for *Lesquerella fendleri.* The resulting model may be employed in any part of the world, using the agroclimatic limits presented in this work. This paper sets the bibliographic basis of statistical modelling of the climate-related crop.

The agroclimatic zoning may useful as a guide to those seeking to develop Lesquerella*.* The best areas for this crop can be observed, as well as non-suitable or suitable areas with irrigation. Farmers interested in planting energy crops, users trying to locate suitable areas and governments interested in fostering promotion measures could benefit from this study.

Since this species is native to the arid and semiarid regions of USA, it could be cultivated in cold and arid environments of different argentine provinces, such as Mendoza, San Juan, La Rioja, San Luis, La Pampa and Rio Negro in rainfed conditions. It could also be implemented with complementary irrigation in part of the provinces of La Pampa, Rio Negro, Neuquén and Chubut, if the purpose is high oil production for industrial and pharmaceutical uses. The development of *Lesquerella* on that widespread area with agro-climatic suitability presents soils of the order Aridisols and Entisols.

It is important to highlight that the agro-climatic suitability map is only indicative and should not be regarded as definitive with respect to individual applications. This map provides the basis for future works, at a higher cartographic scale, which will provide detailed regional guidance for the planting of *Lesquerella spp.*

REFERENCES

Adam N.R., Dierig D.A., Coffelt T.A., Mackey B.E., Wintermeyer M..J, Wall G.W. 2007. Cardinal temperatures for germination and early growth of two Lesquerella species. Industrial Crops and Products. 25, 24-33.

Adamsen F.J., Coffelt T.A., Nelson J.M. 2003. Flowering and seed yield of Lesquerella as affected by nitrogen fertilization and seeding rate. Industrial Crops and Products. 8 (2): 125-131.

Alvarez Prado A.F., Ploschuk E.L. 2008. Development and growth of two Lesquerella species grown under different temperatures during the reproductive period. Industrial Crops and Products 27 (3):400-403.

Brown J., Arquette J. 1994. Lesquerella fendleri, guildelines for cropping. International Flora Technologies, Ltd., Arizona, USA. 8 pp.

Buchanan R.A., Duke J.A. 1981. Botanochemical crops. p. 157-179. In: McClure, TA. and Lipinsky, ES. (eds.), CRC handbook of biosolar resources. Vol. II. Resource materials. CRC Press, Inc. Boca Raton, FL.

Cabido M., 1985. Las comunidades vegetales de la Pampa de Achala, Sierras de Córdoba, Argentina. Documents phytosociologiques 9: 431-445.

Cabido M., Acosta A. 1985. Estudio Fitosociológico en Bosques de Polylepis australes Bitt. ("Tabaquillo") en las sierras de Córdoba, Argentina. Phytosociologiques 9: 387-400.

Cabido M., Acosta A. 1986. Contribución al conocimiento fitosociológico del sub-piso superior de pastizales y bosquecillos de altura de las Sierras de Córdoba. Veröf-Geobot.Inst.ETH, Stiftung Rübel, Zürichi 91: 118-140.

Compton D.L., Laszlo J.A, Isbell T. 2004. Sunscreen active ingredients from Lesquerella oil. American Oil Chemists' Society Meeting. 9-12 May, Cincinnati Ohio.

Correa M.N. 1984. Flora Patagónica, Tomo VIII. Parte IV- Dicotiledóneas dialipétalas (Salicaceae a cruciferae). INTA. Buenos Aires, 559 pp.

Cusimano J.S.P., Hart M.M., Cermak D.M., Cermak S.C., Durham A.L. 2014. Synthesis of Lesquerella α-hydroxy phosphonates. Industrial Crops and Products 53. 236-243

Dierig D.A. 1995. Lesquerella. Available at: http://www.newcrop.hort.purdue.edu/ newcrop/cropfactsheets/lesquerella.html.

Dierig D.A., Adama N.R., Mackey B.E., Dahlquist G.H., Coffelt T.A. 1996. Temperature and elevation effects on plant growth, development and seed production of two Lesquerella species. Industrial Crops and Products. 24 (1), 17-25.

Dierig D.A., Adama N.R., Mackey B.E., Dahlquist G.H., Coffelt T.A. 2006. Temperature and elevation effects on plant growth, development, and seed production of two Lesquerella species. Industrial Crops and Products 24:17-25.

Dierig D., Coffelt T., Nakayama F., Thompson A. 1996. Lesquerella and Vernonia: oilseed for arid lands. Available at: http://www.hort.purdue.edu/newcrop /proceedings1996/v3-347.html.

Dierig D.A., Thompson A.E. 1993. Vernonia and Lesquerella a potential for commercialization. p. 362-366. In: Janick J. and Simon JE. (eds.). New Crops. John Wiley and Sons, Inc. NY.

Dierig D.A., Thompson A.E., Nakayama F. 1993. Lesquerella comercialization efforts in the Unites States. Industrial Crops and Products, 1: 289-293.

Duke J.A. 1978. The quest for tolerant germplasm. p. 1-61. In: ASA Special Symposium 32, Crop tolerance to suboptimal land conditions. Am. Soc. Agron. Madison, WI.

Duke J.A. 1983. Handbook of Energy Crops. Unpublished. Available at: https://www.hort.purdue.edu/newcrop/duke_energy/dukeindex.html

FAO - Ecocrop. 2007. Lesquerella fendleri. Available at: ecocrop.fao.org/ecocrop/srv/en/cropView?id=7258

Foster M. 1999. Lesquerella establishment and response to postemergence herbicides in west Texas. Annual Conference Diversity in Agricultural Markets: New Crops and New Markets. October 17-21. Eugene, Or.

Goodrum J.W., Geller D.P. 2005. Influence of fatty acid methyl esters from hydroxylated vegetable oils on diesel fuel lubricity. Bioresource Technology. 96, 851-855.

Grieve C.M., Poss J.A., Donovan T.J, Francois L.E. 1997. Salinity effects on growth, leaf-ion content and seed production of Lesquerella fendleri (Gray) S. Wats. Industrial Crops and Products, 7: 69-76.

Grieve K.M., Shannon C., Dierig D.A.. 1998. Salinity effects on growth, shoot-ion relations and seed production of Lesquerella fendleri. p. 239-243 In: Janick J. and Simon J.E. (eds.). Perspectives of New Crops and New Uses. ASHS Press.

Hunsaker D.J., Nakayama F.S., Dierig D.A., Alexander W.L. 1998. Lesquerella seed production: water requirements and management. Industrial Crops and Products. 8 (2): 167-1 82

Hyatt L.A., Evans A., Baskin C.C. 2001. Annual dormancy cycles in *Lesquerella fendleri* (*Brassicaceae*) seeds stored under both field and laboratory conditions. p. 648-654. Available at: ttp://www.nrc.ca/cisti/ journals/cjb/b99-142.html

Knothe G., Cermak S.C., Evangelista R.L. 2012. Methyl esters from vegetable oils with hydroxy fatty acids: Comparison of lesquerella and castor methyl esters. Fuel 96, 535-540.

López X., Zbinden A.., Castillo H. 2004. Lesquerella fendleri (Gray) Wats: Yield evaluation at two planting dates and two nitrogen fertilizers level. Simiente 74(1-2): 7-25.

Mazzola M., Kin A., Morici E., Babinec F., Tamborini G. 2008. Efecto del gradiente altitudinal sobre la vegetación de las Sierras de Lihue Calel (La Pampa, Argentina). Bol. Soc. Argent. Bot. 43 (1-2): 103 -119. 2008

Muuse B.G., Cuperus F.P., Derksen J.T.P. 1992. Composition and physical properties of oils from new oilseed crops. Industrial Crops and Products 1: 57- 65.

Novara L.J. 2003. Catálogo de la Flora de la Puna en el Noroeste Argentino. Aportes Botánicos de Salta. Serie Misceláneas. Vol. 2 (1). 56 pp.

Ometto J.C. 1981. Bioclimatology plant. Agronomic Editorial. Agronomic CERES. São Paulo. 440 p.

Ploschuk E.L., Windauer L., Ravetta D.A. 2001. Potential value of traits associated with perennial habit in the development of new oil-seed crops for arid lands. A comparison of Lesquerella fendleri and L. mendocina subjected to water stress. J. Arid Environments. 47 (3): 373-386.

Ploschuk E.L., Cerdeiras G., Windauer L., Dierig D.A., Ravetta D.A. 2003. Development of alternative Lesquerella species in Patagonia (Argentina): potential of Lesquerella angustifolia. Industrial Crops and Products. 18 (1): 1-6.

Roseberg R.J. 1996. Underexploited temperate industrial and fiber crops. p. 60-77. In: Janick J. and Simon J.E. (eds). Progress in New Crops. ASHS Press, Alexandria, VA.

Sanford S.D., White J.M., Shah P.S., Wee C., Valverde M.A., Meier G.R. 2009. Feedstock and Biodiesel Characteristics Report. Renewable Energy Group, Inc. Available at: www.regfuel.com

SIB. Argentine Biodiversity Information System. N/D. Lesquerella mendocina. Available at: http://www.sib.gov.ar/ficha/PLANTAE*physaria*mendocina

Smith C.R., Wilson T.L., Miwa T.K., Zobel H., Lohmar R.L., Wolff I.A. 1961. Lesquerolic acid a new hydroxy acid from Lesquerella seed oil. J. Org. Chem. 26, 2903-2905.

Thompson A.E. 1988. Lesquerella a potential new crop for arid lands. Arid Lands: Today and Tomorrow. EE Whitehead *et al.* (eds) Westview Press, Boulder CO. 1311-1320.

Thompson A.E., Dierig D.A. 1988. Lesquerella a new arid land industrial oilseed crop. El Guayulero 10 (1-2): 16-18.

USDA. 1991. Lesquerella as a Source of Hydroxy Fatty Acids for Industrial Products. Available at: htpp// www.ars.usda.gov/.../Lesquerella/.../LesquerellaBoo.

USDA. 2008. Lesquerella: The Next Source of Biofuel. Available at: htpp//www.csrees.usda.gov/.../impact/2008/.../lequerella.p...

Windauer L., Ravetta D. 1997. La influencia de la temperatura y fotoperíodo en la duración de la fase emergencia floración en Lesquerella fendleri. Available at: http://www.aaic.org/97progrm. htm

Windauer L., Slafer G.A., Ravetta D.A. 2004. Phenological responses to temperature of an annual and a perennial Lesquerella Species. Annals of Botany 94: 139-144. Available at: http://aob.oxfordjournals.org/content/94/1/139.full.pdf

Windauer L., Slafer G.A., Ravetta D.A., Benech-Arnolda R.L. 2006. Environmental control of phenological development in two Lesquerella species. Field Crops Research 96 (2006) 320-327. Available at:
http://www.agro.uba.ar/sites/default/files/publicaciones/Windauer_et_al_2006_Field_Crops_Research.pdf

Zuloaga F.O., Morrone O. (eds). 1996. Catálogo de las Plantas Vasculares de la República Argentina. I. Pteridophyta, Gymnospermae y Angiospermae (Monocotyledoneae). Monogr. Syst. Bot. Missouri Bot. Gard. 60: 1-323.