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Developing an agro-climatic zoning model to determine potential growing areas for *Camelina sativa* in Argentina

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ABSTRACT

The purpose of this paper was the development of an agro-climatic zoning model to determine potential growing areas for *Camelina sativa* in Argentina.

Camelina (Camelina sativa L.) is a promising and sustainable alternative energy crop that belongs to the Brassicaceae (mustard) family. *Camelina sativa* oil contains around 40% fatty acids, of which only a small percentage are saturated. *Camelina sativa* derived biokerosene used in aviation has shown 84% reduction in greenhouse gas emissions during its life cycle, compared to petroleum kerosene. It has the potential of becoming the renewable fuel of choice for air navigation in the future.

Agro-climatology is a valuable tool in the identification of agro-climates with favorable conditions for the introduction of new crops. Agro-climatic zoning permits identifying areas with different potential yields, as per their environmental conditions. It was necessary to evaluate the requirements, limits and bio-meteorological tolerance and conditions for these species, taking into account the climatological characteristics of native areas and regions for their successful cultivation around the world.

In order to define this crop's agroclimatic aptitude in Argentina, climatic data was analyzed from meteorological stations, corresponding to the period 1981-2010.

Finally, *Camelina*'s potential growing areas were obtained with 5 differentiated suitability classes.

Based on international bibliography, the authors outlined an agro-climatic zoning model to determine potential growing areas in Argentina for *Camelina sativa*. This model may be applied to any part of the world, using the agroclimatic limits presented in this paper. This is an innovative work, made by the implementation of a Geographic Information System that can be updated by the further incorporation of complementary information, with the consequent improvement of the original database.

Keywords: Camelina sativa, gold of pleasure, biokerosene, potential growing areas, subhumid to semiarid climate, Argentina

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INTRODUCTION

The aviation industry is committed to reducing its environmental impact and has established ambitious goals to reach carbon neutral growth by 2020 and to reduce carbon dioxide emissions by 50% (from 2005 levels) by 2050. Currently, the aviation industry generates approximately 2% of man-caused carbon dioxide emissions; it is a small but growing share, projected to reach 3% by 2030.[1]

The International Air Transport Association[2] encourages its member airlines to use 1% and 10% alternative fuels by 2015 and 2017, respectively. However, the target of aeronautics is to achieve "zero carbon growth" through the use of biofuels.[2]

Airlines are also committed in this respect. Globally, they created the Sustainable Aviation Fuel Users Group (SAFUG), an organization focused on accelerating the development and commercialization of sustainable aviation biofuels.

Argentina occupies the fourth place in biodiesel production, after Germany, France and Brazil. Nowadays, soybean (*Glycine max*) is the country's most important agricultural cultivation. Exports of its grains and sub-products generate very high economic income, higher than any other agricultural or livestock production. It constitutes a significant proportion of the foreign currency that enters the country. The agricultural season of 2014 is expected to surpass 20 million soybean-cultivated hectares. This "soybean boom" started in 2002 and it continues with a marked steady increase in cultivated areas. The biodiesel industry in Argentina uses soybean oil as its main feedstock, representing more than 95% of processed totals.

Argentina stands as a great promise for helping the world alleviate fossil fuel dependence in aviation, using *Camelina sativa* as feedstock to produce biokerosene in lands beyond traditional agricultural areas.

Camelina (Camelina sativa L.) is a promising sustainable alternative energy crop that belongs to the Brassicaceae (mustard) family. It is also known as *C. microcarpa* and *Myagrum sativum* (synonyms). It is commonly known as gold of pleasure, French turnip, bastard sesame, false flax, golden flax (English), *nagami-no-ama-nazuna* (Japanese), *ya ma ji* (Chinese), *yanicnik siaty* (Slovak) and *camelina* (Spanish).

Camelina is a native plant from the Mediterranean and Central Asia. It has been harvested for 4000 years. Its cultivation probably originated in Europe and it has been used as vegetable fuel oil. *Camelina* oilseed was grown extensively in Northern Europe until the 1950's, increasing fuel prices coupled with a 'diet-conscious' society have revived interest in *camelina* for food and biofuel uses.[3] The Soviet Union was the largest producer of the twentieth century.[4]

Camelina sativa is also found as a weed in the Northern Hemisphere from 36° to 70° North Latitude. It is one of the main weeds attacking flax. Seeds do not have a latency period and they generally do not infect other crops.[5] In Argentina, *camelina* has been recognized as a weed in Buenos Aires, Córdoba, La Pampa and Santa Fe.[6]

Camelina grows well in temperate climates and requires early planting in order to obtain maximum yields. It reaches heights of 30 to 90 cm. The stem ramifies and becomes woody once it matures. Its leaves are shaped arrows and its fruits are similar to flax balls. The seeds are very small, pale yellow and brown, oblong and rough; 1000 seeds weigh between 0.8 and 2.0 grams.[7] As seed pods do not open, losses during harvest are minimal.

The *Camelina sativa* population found in a given flax crop mimicked the size and shape of flax seeds, as reported by Sinskaia et al.[8] *Camelina* seeds, with aerodynamic features similar to flax (*Linum usitatissimum* L.), were selected by ventilation processes used on seed mixtures before sowing.

Seeds have between 33 and 42% oil content: 30 to 40% linoleic acid, 15% eicosenoic acid, and less than 4% erucic acid. In addition, it is similar to flax in proteic composition, with higher sulphurous content.[5,9]

Oil extracted from *camelina* seeds present a high ratio of fatty acids rich in Omega-3 (38% volume of total fatty acids), therefore it could be used for human food consumption.[9] Zubr and Matthaus,[10] reported that camelina oil contains an average of 28.07 ppm of alpha tocopherol (α-T), 742 ppm of gamma tocopherol (γ-T), 20.47 ppm of delta tocopherol (δ-T), and 14.94 ppm of plastochromanol. Total tocopherols' average content was 806 ppm.

Omega-3 obtained from *camelina* oil is more stable than omega-3 obtained from fish. It has been used in dressings and mixed with vinegar; with the resulting mixtures being stable for many months at room temperature.[7] As its resistance to oxidation and the storage stability is low at high temperatures, it is best suited for use in cold dishes.[9]

The oil was first sold in Europe for cooking and dressings, but it has low stability at high temperatures. It was also used in cosmetic, personal care and mild detergent industries. Furthermore, it has been used as a substitute for petroleum derivatives, as adjuvant and for pesticide sprayers.[5] Bio-lubricant *camelina* oil can be converted into a wax ester that could replace more expensive, and less available, jojoba waxes in industrial and cosmetic products.

Biotehgen (Microbial Biotechnology Center) is working on a new *camelina* variety with higher oil content. Research for this new variety has already started and the results are very promising.

The flour remaining after oil extraction is similar to soybean flour, containing 45 to 47% of raw protein and 10 to 11% of fiber.[10]

Camelina sativa biodiesel properties have already been fully described. Biodiesel, as well as seed oil, have been used in engine trials with promising results.[11]

The biokerosene of *camelina* occupies a privileged position as the renewable fuel of choice for airline companies, since the American Society for Testing and Materials (ASTM)[12] approved its technical specifications. ASTM D1655 specifies that fuels used for aircraft should not have freezing points above − 40°C. Biokerosene obtained from *camelina* has been successfully tested in the Air Force, Navy, U.S Army, Japan Airlines, Iberia and Embraer, among others. Several trials have been performed on different kind of aircrafts and engines at different speeds. Biokerosene from *camelina sativa* used in aviation has shown an 84% reduction in greenhouse gas emissions (GGE) during life cycle, compared to petroleum kerosene. Moreover, as every biofuel, it contains fewer impurities, thus allowing a better sulfur dioxide and soot reduction than the current technology of fossil fuels.[13] The U.S. Environmental Protection Agency (EPA) assures that GGE produced by *camelina*, throughout its life cycle, are very similar to those associated with soy biodiesel. According to Michigan Technological University, GGE reduction owes to *camelina* unique features: low fertilizer consumption, high oil yield and co-products availability, such as flour and biomass.

Updated estimates of *camelina* cultivation requirements and commercial scale oil recovery and refining were used to calculate life cycle greenhouse gas emissions and energy demand for both hydrotreated renewable jet fuel and biodiesel. Greenhouse gas life cycle emissions for biodiesel and hydrotreated renewable jet fuel are 18.0 and 22.4 g CO_2 equiv/MJ fuel, which represent savings related to petroleum counterparts of 80% and 75%, respectively.[14]

Camelina produces high quality biodiesel. Oils with high proportion of unsaturated fatty acids improve operability at low temperatures, but reduce oxidation stability, resulting in a high iodine index. Iodine index meeting European standards varies between 140 and 160, thus qualifying it as drying oil.[5] Most fatty acids in *camelina* biodiesel are unsaturated, only 12% are saturated. Polyunsaturated fatty acids make up 54% and are mostly comprised of linolenic acids, while 34% are monounsaturated acids, with prevalence of oleic and eicosenoic acids.

Volatile isothiocyanates have not been found in *camelina* flour,[10,15,16] a situation that does not occur with crambe flour (*Crambe abyssinica*) or industrial rape flour. The low glucosinolate content means it could be used for animal feed provided, like soy, it presents 45 to 47% crude protein and 10 to 11% fiber.

Keske et al.[17] concluded that *camelina* could offset on-farm diesel use, making it economically feasible for farmers to grow their own fuel. As a result, *camelina* production may increase farm income, diversify rural economic development, and contribute to the attainment of energy policy goals.

Ecological requirements

There are several winter annual biotypes in the available germplasm, and it is possible to cultivate *camelina* as a winter crop under mild winter conditions, and also as spring crop in zones with severe winter conditions.

Camelina farming is optimal in zones where flax is cultivated. It is cold resistant and drought tolerant, but it does not tolerate excessive heat conditions during flowering period.[18,19]

Camelina is a short-cycle species (85 to 120 days), well adapted to production at temperate climatic zones. It has been demonstrated that this species germinates at temperatures of 1 to 20°C.[20] In Oregon, it has germinated at 3°C soil temperature[21] and plants are very tolerant to white frosts. In Montana, *camelina* showed no damage at -11°C. Seedlings resisting different frost conditions at rosette stage have been observed.[20]

Camelina cultivation adaptability depends on the climate.[22] The range of average temperatures through its life cycle varies between 15 to 25°C, while precipitations at origin or cultivation areas annually oscillate from 300 to 1800 mm. During its vegetative cycle, optimal temperatures range between 10 and 24°C, while during its reproductive development (flowering, seed filling), they range between 24 and 32°C.[22]

Robinson[5] has demonstrated that *camelina* could be cultivated without previous tillage and without herbicides, giving better results than conventional flax growing. *Camelina* can also be cultivated on frozen soils in autumn, late winter or at spring beginning, producing good yields. In addition, *camelina* can be incorporated to rotation, allowing double cropping during the year. It seems that suitable moisture and cool temperatures, especially during flowering-maturity period, favor oil content and its quality. At flowering stage, the plant requires no less than 140 mm water in order to get good yields (water critical period).[23] According to Pavlista et al.,[24] the optimal conditions should be: 150 mm during the vegetative period and 200 mm during the reproductive period.

Compared to flax, *camelina* can compensate better from early water deficiencies[18]: it also adapts better to dry zones than other oleaginous.[25] The response to watering varies through the different development stages. Vollmann et al.,[19] have evaluated the agronomic performance of 32 genotypes in Austria and they concluded that hydric stress during flowering period reduces yields, while enough watering during seed filling, raises oil content.

MATERIALS AND METHODS

Agro-climatic zoning permits the identification of areas with different potential yields, as per their environmental conditions. Every plant is sensitive to weather conditions. They have minimum as well as maximum requirements, as far as weather conditions are concerned, in order 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”.[26]

The first author has long experience in agro-climatic zoning of energy crops in Argentina.[27–30] This paper intended to develop an agro-climatic zoning model to determine potential growing areas for *Camelina sativa* in Argentina. For this purpose, it was necessary to identify the requirements, limits and bio-meteorological tolerance and conditions for this species, taking into account the climatological characteristics of native areas and the regions of successful cultivation around the world.

In order to define this crop’s agro-climatic aptitude in Argentina, the climatic data from meteorological stations was analyzed, corresponding to the period 1981–2010.

Based on the above mentioned bibliography, thermal and hydric limits were defined in order to describe suitable classes.

In a first step and in order to analyze the bioclimatic requirements of *Camelina sativa*, attention was focused on the moisture factor. Analyzing the average annual isohyets of 350 and 500 mm: the annual average values observed in Montana and Idaho, respectively, where *Camelina* is successfully cultivated. However, optimal conditions occur when the plant receives 150 mm during vegetative growth and 200 mm during reproductive development.[19] These requirements were also taken in account to define suitable classes.

Two sub-periods were defined to consider thermal factors: vegetative period that extends from mid August to mid October, and reproductive season that runs from mid October to mid December. For this purpose, isotherms corresponding to the average temperature of each period were taken into account.

For the vegetative period, different temperature ranges were considered. In this way, ranges below 7°C were described as marginal area; from 7 to 10°C were qualified as suitable areas; from 10 to 24°C were defined as optimal areas[22] and above 24°C, non-suitable areas. In order to describe thermal capacity during reproductive season, marginal areas with temperatures below 10°C were considered; optimal areas are those with temperature ranges between 24 and 32°C,[22] whereas temperature ranges from 32 to 38°C are also marginal areas, given their excessive temperatures.

Using geographical limits for different variables, aptitude types were defined: optimal areas (annual precipitation >500 mm, accumulated precipitation August to mid December >350 mm, average temperature during growing period >10°C and average temperature during reproductive period from 10–22°C); Very suitable areas (>500 mm of annual precipitation, 350 mm accumulated precipitation August to mid December, average temperature during growing period >10°C and average temperature during reproductive period from 7–10°C); Suitable areas under humid regime (>500 mm of annual precipitation, average temperature during growing period >10°C and average temperature during reproductive period from 10–22°C); Suitable areas under sub-humid to semiarid regime (350–500 mm of annual precipitation, average temperature during growing period >10°C and average temperature during reproductive season from 10–22°C); and Non suitable areas (annual precipitation <350 mm).

The agro-climatic zone map was obtained by overlaying previous ones. To obtain the maps, a series of previously interpolated bioclimatic variables were used, afterwards these 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 GIS of the Arc-GIS 9.3 Program, following the Ordinary Kriging interpolation method.

Figure 1 (Argentina's political map, with provincial toponymy) was included in order to construct areas classified according to their different grades of agro-climatic fitness.

Figure 1. Argentina's political map.

RESULTS AND DISCUSSION

In order for this paper to be understood by researchers all over the world and to facilitate the comprehension of the agro-climatic zoning results, here follows an explanation of Argentina's different weather conditions.

Due to its vast territory, Argentina presents a remarkable climatic diversity. In this sense, various geographic factors have a direct bearing on determining the different regions' climatic characteristics. One such factor is latitude: the Argentine Republic is characterized by its great latitudinal development:

from 21°46′ to 55°58′ S. This is basically the origin of the country's climatic variation. The Andean Mountain Range that extends from North to South in the Argentine West, is a relief factor that facilitates the circulation of air masses to the East and determines different winds.

The presence of the Atlantic Ocean, which constitutes a natural border to the East, exercises a moderating action diminishing the thermal range.

Different meteorological factors act on Argentine territory, some are local whereas others originate beyond the Argentine borders. This is the cause of the warm and humid winds coming from the Atlantic anticyclone, and affects the regions located to the north of Patagonia or the west winds coming from the Pacific anticyclone, as well as cold winds from the Antarctic anticyclone. As shown below,

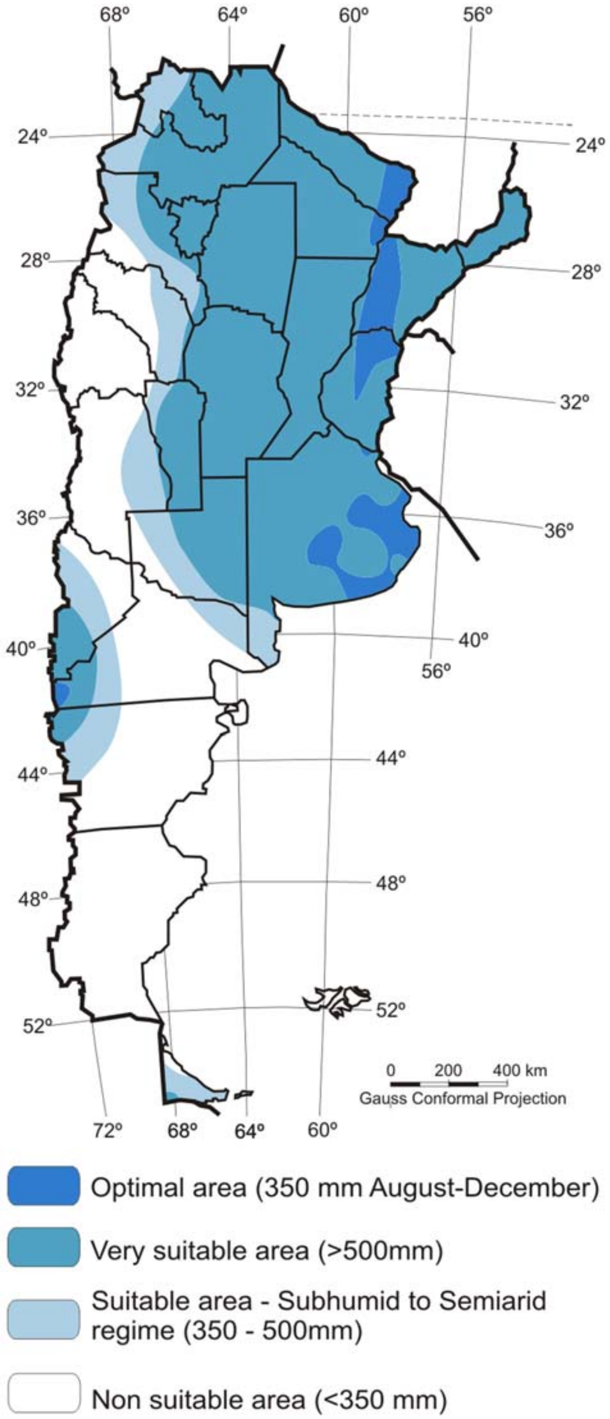

Figure 2. Annual and accumulated precipitation during the growing season (August–December).

Figures 2, 3 and 4 indicate the spatial variation of the geographical limits of different bioclimatic variables, that define the suitability classes.

Figure 2 represents the moisture regions. Four classes of suitability were defined (optimal, very suitable, suitable and non-suitable) considering annual and accumulated precipitations during reproductive and vegetative periods, defined on the base of the species bioclimatic requirements.

Optimal areas receive 150 mm of precipitation during growing period and 200 mm during reproductive development. This means an accumulated rainfall during the period mid August – mid December equaling or exceeding 350 mm.

Very suitable areas are located at the eastern humid region and the northwestern region, which receive from 500 to 1600 mm annual precipitation. Isohyet values decrease from east to west due to the oceanic influence being reduced towards the west and to the foothills of the mountainous relief.

It should be pointed out that both the 350 ppm and 500 ppm isohyets follow a route parallel to the Parana River. This precipitable water comes from the South Atlantic anticyclone and discharges

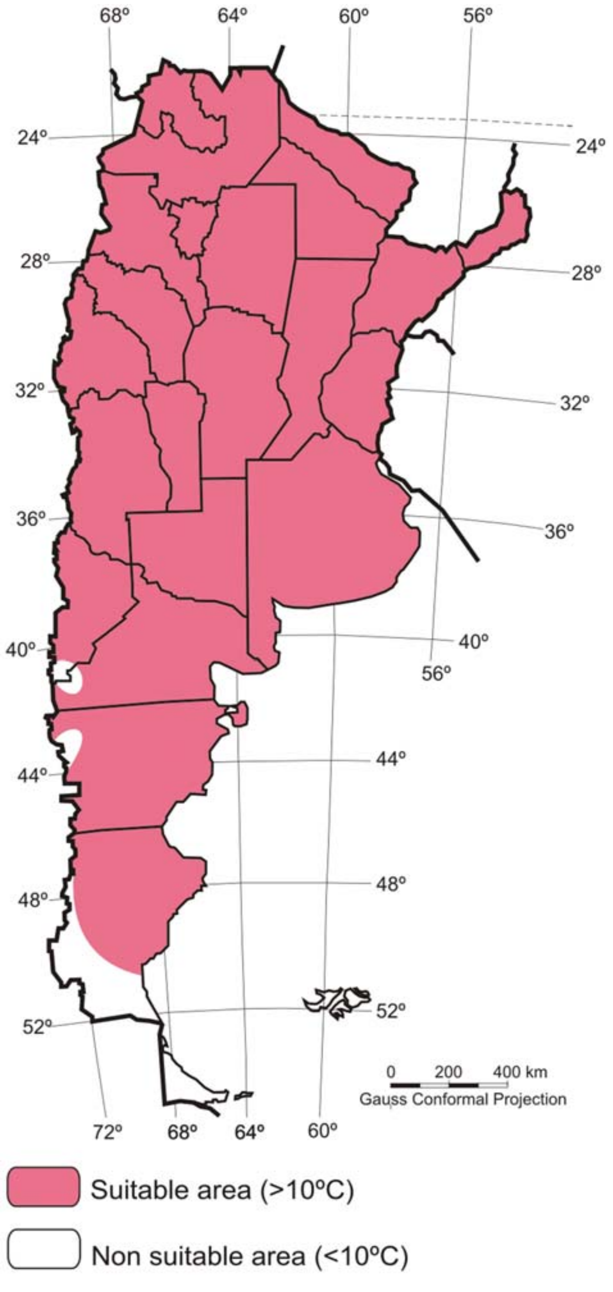

Figure 3. Average temperature of growing period.

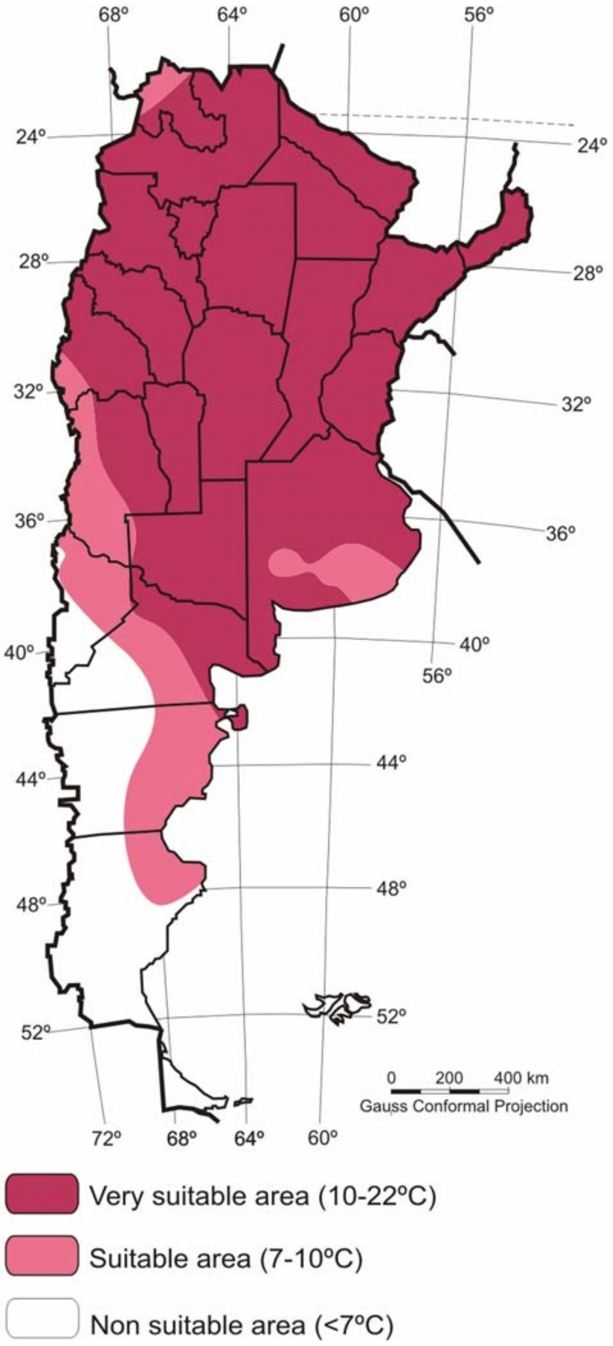

Figure 4. Average temperature of reproductive development.

humidity as it moves towards the West. The Andean-Patagonian Forest also appears as an optimum and very suitable area. There, the mountain range losses altitude and the transversal valleys allow the entrance of the humidity coming from the South Pacific anticyclone, thus creating a humid zone, very suitable for agriculture.

Towards the west of the very suitable eastern area there is a narrow strip of land, suitable under ‘sub-humid to semiarid’ regimes. This zone goes from Jujuy (in the North) to the south of the province of Buenos Aires. Towards the east of the Patagonian ‘very suitable’ area, there is a ‘suitable’ area (350 – 500 mm of annual precipitation) that comprises part of the provinces of Neuquén, Rio Negro and Chubut. There is a third ‘suitable’ area in the province of Tierra del Fuego.

Figure 3 and Figure 4 show the thermal regions. Figure 3 shows the average temperature of the growing period, which extends from August to October, where two classes of suitability were defined (suitable and non suitable areas). In general terms, Argentina has a mild-temperate climate, i.e. there are no optimal areas at the end of the winter (August) and commencement of spring (mid October), with a thermal average of 24 to 32°C. This season presents frequent polar air irruptions from the Antarctic anticyclone causing frost throughout country. This figure, however, shows that most of the territory exhibits suitable conditions.

Figure 4 presents the average temperature of the reproductive season. This figure shows three applicable classes (very suitable, suitable and non- suitable areas) for different thermal limits, corresponding to the average temperatures of the reproductive season. Very suitable areas are found in the country's Northeast, North and Center, with the southern border being the eastern region of the province of Río Negro and the Valdés Peninsula in the province of Chubut. The Northwest of Jujuy and the central and southern regions of Buenos Aires are excluded due to the altitude factor. Colder temperatures in the province of Buenos Aires are generated by the low hills of Tandilia and Ventania (relief influence temperatures, where the higher the altitude, the lower the temperature). The latter are also affected by the cold ocean current coming from the Falkland Islands. Other suitable areas can be found in the West of the country (provinces of Mendoza and San Juan) and a great part of the Patagonian region that comprises the provinces of Neuquén, Rio Negro, Chubut and Santa Cruz.

The agro-climatic zone map was then obtained by overlaying the previous maps. Figure 5 shows potential growing areas for *camelina* cultivation, classified as; optimum, very suitable, suitable and non-suitable areas.

Optimal areas cover the eastern region of the provinces of Chaco and Formosa, the western region of Corrientes, northern and central regions of Entre Ríos and central and eastern regions of Buenos Aires. There, annual precipitation during the growing period amounts to >500 mm, accumulated precipitation during August to December ranges >350 mm and average temperature during growing period reaches >10°C,while during the reproductive period oscillates from 10–22°C.

Very suitable areas can be found in the eastern and southeastern regions of the province of Buenos Aires. These areas are characterized by annual precipitation >500 mm, accumulated precipitation during August –December >350 mm, average temperature during growing period >10°C and average temperature during reproductive period from 7–10°C.

Suitable areas under the humid criteria show annual precipitation >500 mm, average temperature during growing period >10°C and average temperature during reproductive period from 10–22°C. These areas under humid climate conditions are currently destined for food crops, therefore *camelina* cultivation for biokerosene or biodiesel production is out of the question. The situation would be different if *camelina* were meant for oil food production, taking advantage of its richness in Omega-3. This is an issue of economic profitability.

Suitable areas under sub-humid to semiarid criteria receive annual precipitation from 350 to 500 mm, with an average temperature during the growing period of >10°C, and during reproductive season ranging between 10–22°C. This is the zone where *camelina* production for energy purposes should be cultivated. This area covers part of Neuquen, West of Salta and Jujuy, part of La Rioja, Catamarca, East of Mendoza, Northwest of San Luis, Center of La Pampa, Northeast of Río Negro and South of Buenos Aires. This zone is called " bushy steppe" and presents frequent frosts.

Non-suitable areas receive <350 mm of annual precipitation. No complementary irrigation is recommended for *camelina* because the intensive extraction of water to irrigate this or any other energy crop could affect the availability of this resource, especially in areas with shortage problems. That is why the basic premise for the production of biofuels is to use low-productivity lands so as not to compete with the food market. The use and value of water in agriculture must be destined for food.

CONCLUSIONS

Based on international bibliography, the authors were able to delineate this agro-climatic zoning model to determine potential growing areas for *Camelina sativa* in Argentina. This model may be used in any part of the world, considering the agroclimatic limits presented in this paper.

The existence of a large area with suitability for the cultivation of *Camelina sativa* has been demonstrated. Therefore, there are real possibilities for *camelina* to be successfully cultivated in Argentina, because of its rusticity and resistance to low temperatures.

Argentina possesses agroclimatic suitability under sub-humid to semiarid climates to produce *Camelina sativa* as an energy crop. Thus, Argentina has the capacity "to harvest biokerosene" for air navigation use under a sub-humid to semiarid climate, located in the provinces of Neuquén, Salta,

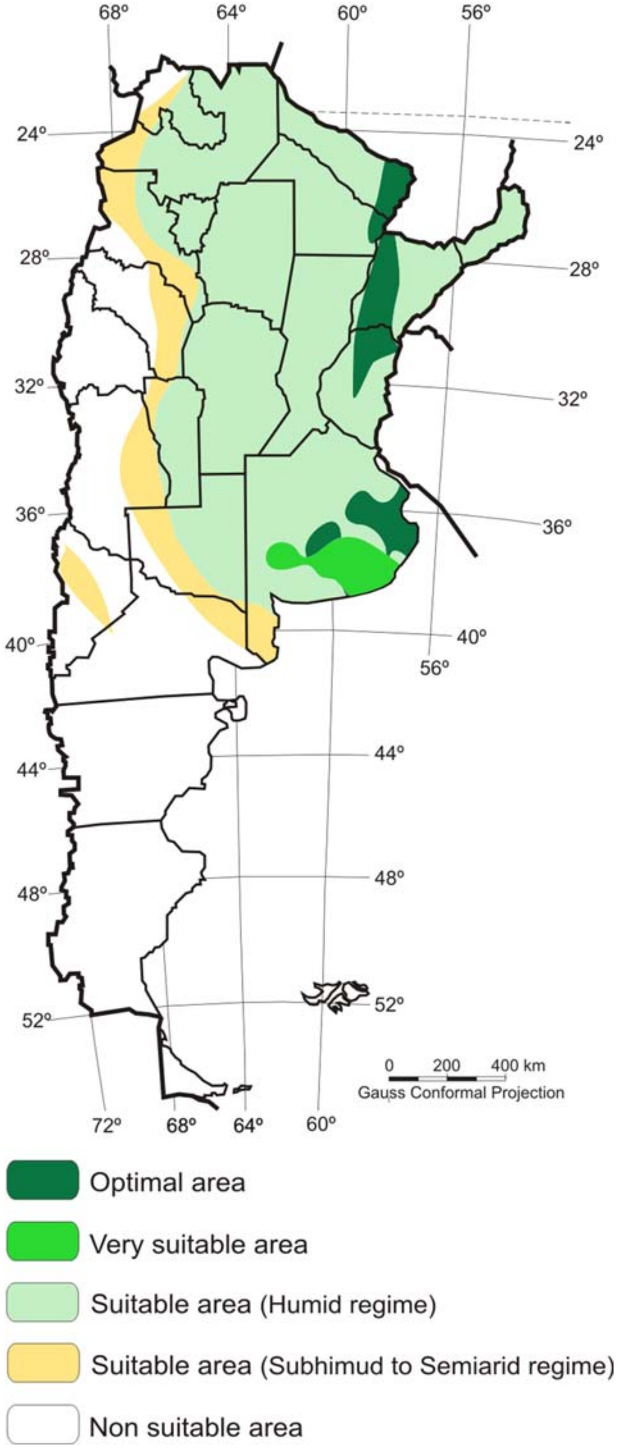

Figure 5. Potential growing areas for *Camelina sativa*.

Jujuy, La Rioja, Catamarca, Mendoza, San Luis, La Pampa, Río Negro and Buenos Aires. These lands, classified as suitable at the agroclimatic suitability map, could be used for cultivation of *camelina* for energy purposes, based on the knowledge that such lands are not intended to compete with those devoted to food crops.

Economic and profitability features would obviously play a leading role in the motivation of farmers, as in this research we only considered the agro-climatic variables. This crop may generate new business opportunities in Argentine rural areas, thus providing additional diversity and innovation and a more sustainable food chain.

The *camelina* crop does not significantly differ from food crops, although its additional potential environmental benefits could help to deliver a more sustainable farming sector, contributing to society's wider needs.

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