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Land Suitability Assessment for Camelina (*Camelina sativa* L.) Development in Chile

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Abstract: Camelina (*Camelina sativa* L.) is an oilseed with potential for use as a raw material in second-generation biofuels. Camelina has a seed yield of up to 2380 kg·ha^{-1} and contains around 45% fatty acids. Selection of a suitable site is critical for production optimization. The objective of this study was to determine Chilean agro-climatic suitability for establishing camelina as a productive alternative. Climate and soil requirements and geographical restraints were evaluated for the species, considering the climatological characteristics of its regions of origin, as well as regions where camelina is successfully grown in the rest of the world. The variables considered included factors (maximum temperatures of the warmest month, water deficits, and degree days) and limitations (altitude, geomorphology, and current land use), which permitted the evaluation of the national territory for a certain level of suitability. It was determined that 1.3% of the national territory (960,664 ha) has some degree of suitability for camelina adoption. Between the Biobío and Los Lagos regions, 49.0% of the land (471,203 ha) is in the category of no thermic restrictions, with mild water restrictions, and mild soil restrictions or without information, which can be used for camelina production. The Los Ríos region has 21.4% surface area (321,176 ha) with some level of suitability for camelina, the most suitable region to establish this crop in Chile. This research has provided valuable information applicable to new species and geographic areas which facilitate the adaptation of agricultural and forestry production to global changes.

Keywords: bioenergy; *Camelina sativa*; energy crops; agro-climatic suitability; biodiesel

1. Introduction

Camelina (*Camelina sativa* L.) is a member of the Brassicaceae family [1]. It has been cultivated for centuries as an oilseed crop for human food [2]. The high oil content in camelina seeds increases the plant's potential as a new source of biofuel [3,4]. Camelina is an annual herbaceous plant, which can sometimes act as if it is biennial. In its maturity, it can measure between 60 and 120 cm in height [1,5]. Its fruit is a pear-shaped, indehiscent silique [1] and can reach between 5 and 6 mm in diameter. Each silique contains between eight and 15 seeds, each of which is very small, measures around 2 mm in length, and has a golden or brown color [1,5].

Camelina seeds contain between 30% and 45% oil, and over 80% of the fatty acids in this oil are unsaturated [6,7]. Of these fatty acids, the main fatty acids are linolenic (27.9%–39.7%), linoleic (13.5%–18.7%), oleic (14.2%–17.5%) and gondoic (15.1%–16.4%). Erucic, palmitic, oleic, arachidic, eicosadienoic, and eicosatrienoic acids are also found [6,7]. Camelina oil has characteristics that distinguish it from other vegetable oils; above all, it has high α-linolenic acid content, which is an essential fatty acid and is added to foods [8]. However, camelina oil also contains erucic acid, which can have negative effects on animal growth and development [6]. The presence of erucic acid has led to improved rapeseed varieties, obtaining the canola variety (with low erucic acid and glucosinolate contents) in the 1970s [9].

The geographic origin of camelina is not precisely known, though its predecessors existed in three distribution areas: the region surrounding the Mediterranean Sea, Northern Europe, and East Asia [1]. It was an important oilseed until the mid-20th century and was produced in several European countries, particularly in the central and northern continent, though its production declined afterward [2,6]. Recently, interest in this species has grown and many diverse studies have been undertaken to evaluate its adaptability in different agro-climatic conditions [2,10–15].

Zubr [2] tested seven summer varieties in different locations of Northern Europe and Scandinavia, and found that the results were more influenced by climate and soil conditions than by the origin or strain used. The average oil content in camelina varieties was 42.1% and the average protein content was 43.3% [2]. Angelini et al. [10] evaluated camelina in a Mediterranean climate, in Pisa, Central Italy, and it reached a maximum oil content of 33%. This case showed that the oil content dramatically decreases when high temperature/low precipitation events exist, reaching 23.6%. Despite this, seeds with a high oil content (41.4%) have successfully been produced in Maricopa, Arizona, as a winter crop for the Northern Hemisphere [11]. In this case, the yield per hectare was low, reaching approximately 1000 $kg \cdot ha^{-1}$ [11], which is much lower than that obtained by Vollmann et al. [12], who found over 2200 $kg \cdot ha^{-1}$.

Winter [13], spring [14,15], and autumn-sown [15] varieties have been evaluated in the northern United States as low-cost productive alternatives. Gesch and Cermak [13] conducted their studies in Morris, Minnesota, sowing two winter varieties between September and October. They reached seed yields of up to 1300 $kg \cdot ha^{-1}$, with oil contents between 28.2% and 42.0%. Meanwhile, Gesch [14] obtained between 780 and 1800 $kg \cdot ha^{-1}$, with oil contents between 37.7% and 41.6%, using the same study location, but sowing spring cultivars between April and June. Guy et al. [15] tested 18 distinct genotypes, sown during different seasons (spring and autumn) and in different locations. They obtained 25% higher yields when camelina was sown in spring compared to autumn sowing. In addition, they determined that camelina is sensitive to drought. When precipitation was lower than 200 $mm \cdot year^{-1}$, the yield was 127 $kg \cdot ha^{-1}$, whereas when precipitation was 580 $mm \cdot year^{-1}$, the yield was 3300 $kg \cdot ha^{-1}$.

In Chile, three spring varieties were planted in the central southern regions with five different locations and sowing dates. The highest average yields were obtained in Los Angeles and Osorno, with 1600 $kg \cdot ha^{-1}$ and 1552 $kg \cdot ha^{-1}$, respectively, though Osorno gave the highest absolute yield of 2314 $kg \cdot ha^{-1}$ when sown in May. Oil production was between 39.8% and 45.8% [5], close to the maximum oil production value of 48%, obtained via elite ecotype selection [12].

Camelina has low nutritional requirements. The oil content of its seeds decreases as it releases nitrogen into the soil, and it is not replenished after fertilization with phosphorus and sulfur [16]. Camelina has a higher tolerance to drought, frost, and heat, and is less susceptible to pests and disease when compared to canola [15,17]. It is also more adaptable to marginal soils [16] and has lower production costs [4], contributing to environmental sustainability and climate change mitigation [18].

Camelina is appreciated for its high adaptability to diverse conditions, though it varies depending on the variety used and the harvest season, as well as the local soil and climate conditions. In Chile, high experimental productivity has been achieved, with high oil contents, making it an interesting productive alternative that could contribute to second-generation biofuel production. The present study determined the Chilean territory potential for camelina cultivation, considering its climate and soil requirements, as well as the availability of existing territory in Chile, avoiding competition with current land uses.

2. Materials and Methods

2.1. Materials

Climate mapping used was based on the Bioclimatic Atlas of Chile [19]. The maps of soil orders were obtained from the Soil Map of the World [20]. The current land use, protected wilderness areas, and other data were obtained from the Environmental Information National System [21].

2.2. Climate Adaptable Ranges

A bibliographic review was made in the area where camelina naturally develops, as well as where it has been introduced and produced successfully, and the presence of climate data was determined for each location where the species is registered. The following variables were considered: Monthly average minimum temperature (°C), monthly average maximum temperature (°C), relative average monthly humidity (%), and monthly precipitation (mm). This information was recorded and later used to determine the variables derived from degree days (*DD*, Equation (1)), potential evapotranspiration with Ivanov's method (*ETp*, Equation (2)) [22,23] and water deficit (*WD*, Equation (3)).

$$DD = \sum_{i=m}^{n=m_f} \left\{ nd_i \times \left[\left(\frac{tx_i + tn_i}{2} \right) - t_u \right] \right\} \tag{1}$$

where DD are degree days; m is the month of the period under consideration; m_f is the final month of the period under consideration; nd_i is the number of days in month i; tx_i is the average maximum temperature of month i (°C); tn_i is the minimum average temperature of month i (°C); and t_u is the threshold temperature (°C). The threshold temperature depends on the altitude and latitude where the registered specimen is found, which can be 5 °C (latitude above 46° and altitude above 2000 m), 7 °C (latitude between 28° and 46° and altitude between 1500 and 2000 m) or 10 °C (latitude below 38° and altitude below 1500 m).

$$ETp = \sum_{i=m}^{n=m_f} 0.0018 \times \left\{ \left[25 + \left(\frac{tx_i + tn_i}{2} \right) \right]^2 \right\} \times (100 - RH_i) \tag{2}$$

where ETp is the potential evapotranspiration (mm·year^{-1}); m is the first month of the year; m_f is the last month of the year; tx_i is the maximum average temperature of month i (°C); tn_i is the minimum average temperature of month i (°C); and RH_i is the relative humidity of month i (%).

$$WD = P - ETp \tag{3}$$

where WD is the water deficit (mm·year^{-1}); ETp is the potential evapotranspiration (mm·year^{-1}); and P is the average annual precipitation (mm·year^{-1}).

Camelina's adaptable ranges were subsequently determined for each climatic variable.

2.3. Soil Adaptable Ranges

A scientific publication review was realized for establishing locations of production with information about soil characteristics (according to United State Department of Agriculture (USDA) or Food and Agriculture Organization (FAO) classifications), and yields achieved were indicated for each site. These were classified based on production levels registered by soil type, and labeled as without restriction, mild restriction, moderate restriction, and restricted. The "without information" label was used for cases where there were no existing production records regarding different soil types.

2.4. Agro-Ecological Zoning

Agro-ecological zoning was determined according to the guidelines for land evaluation given by FAO [24] and Rossiter [25]. National territory suitability was determined, selecting attributes and establishing different aptitude levels for camelina development. These are considered factors associated with climatic and soil requirements of camelina with their respective ranges or levels of aptitude, in addition to limiting associated with land use, altitude, and geomorphological position.

Factors were analyzed according to level of restriction that they present (without restriction, mild restriction, moderate restriction, and restricted), whereas limiting was evaluated by maintaining the level of restriction or by removing the possibility of using this territory via multiplication of the maps [25,26].

This information was processed using Geographic Information System (GIS), ArcGIS® 10 (Esri, Redland, CA, USA, http://www.esri.com/software/arcgis), through decision rules based on Boolean operators using top-down logic [27]. A map with different aptitude levels was obtained according to a combination using restriction levels of every factor and its limiting.

3. Results

3.1. Climatic Information

The presence of camelina was registered in 27 locations for which climatic information was available (thermic and water; Table 1), including where it occurs naturally and where it has been introduced for productive purposes. The information obtained from these 27 locations was used to determine the critical factors for camelina adaptation.

Table 1. Cities or towns where camelina is present, which were used to determine the soil and climate requirements for its development.

Country	City/Town	Geographic Coord.		Reference
		Latitude	Longitude	
Germany	Müllheim	47°48′N	007°37′E	[2]
Germany	Soest	51°34′N	008°06′E	[2]
Denmark	Taastrup	56°07′N	009°59′E	[2]
Scotland	Aberdeen	57°08′N	002°05′O	[2]
Finland	Helsinki	60°10′N	024°56′E	[2]
England	Tadcaster	53°52′N	001°15′O	[2]
Ireland	Knockbeg	52°51′N	006°56′O	[2]
Sweden	Uppsala	59°51′N	017°38′E	[2]
Chile	Gorbea	39°05′S	072°40′O	[5]
United States	Rosemount	44°44′N	093°07′O	[6]
Italy	Pisa	43°40′N	010°19′E	[10]
United States	Maricopa	33°03′N	112°02′O	[11]
Austria	Gross Enzersdorf	48°11′N	016°33′E	[12]
United States	Morris	45°35′N	095°54′O	[14]
United States	Lewiston	46°23′N	116°58′O	[15]
United States	Pendleton	45°43′N	118°37′O	[17]
Argentina	Ensenada	34°55′S	057°57′O	[28]
United States	Cass	38°38′N	094°21′O	[28]
United States	Jackson	39°06′N	094°30′O	[28]
United States	Saint Louis	38°38′N	090°14′O	[28]
France	Doullens	50°09′N	002°20′E	[28]
Canada	Swift Current	50°17′N	107°47′O	[29]
Canada	Lethbridge	49°41′N	112°50′O	[29]
Slovenia	Prevalje	46°32′N	014°52′E	[30]
United States	Scottsbluff	41°50′N	103°41′O	[31]
United States	Wyarno	44°48′N	106°46′O	[32]
Lithuania	Vėžaičiai	55°43′N	021°27′E	[33]

The factors considered for camelina adaptation were: maximum temperature of the warmest month (TMX), January and July in the Southern and Northern Hemispheres, respectively; degree days during the productive cycle (DD), considered to be 221 days in the trials run in Chile [5]; and water deficit (WD, Table 2).

Table 2. Critical thermic and water ranges for camelina adoption in Chile.

Parameters	Aptitude	Range of Aptitude
TMX (°C)	Restricted	<21; >31
	Mild restriction	21–23.5; 28.5–31
	Without restriction	23.5–28.5
DD	Restricted	<500
	Mild restriction	500–750
	Without restriction	>750
WD (mm)	Restricted	<–500
	Moderate restriction	–500–(–250)
	Mild restriction	–250–0
	Without restriction	>0

TMX: Maximum temperature of the warmest month; DD: Degree days; WD: Water deficit.

3.2. Thermic Factors

The intersection of thermic factors (TMX and DD) determined the existence of over 30 million ha nationwide with varying levels of thermic suitability (Figure 1a). Lands without thermic restriction were 92.3% of the total area with thermic suitability, which are mainly located in north central Chile (65.1% of the total area without restriction). The Coquimbo and Valparaíso regions possess the greatest surface area with some level of suitability, between 73.1% and 73.7% of the total regional territory. In the O'Higgins region, 98.7% of the land area with some level of suitability is classified as without restriction. Additionally, the Aysén and Magallanes regions did not present territory with any level of suitability, while only 6.1% of the Los Lagos regional territory has any degree of suitability for camelina cultivation, 2.8% of which is labeled as without restriction.

3.3. Water Availability Factors

Contrary to what occurred with the intersection of thermic factors, the water availability factor showed a tendency toward south Chile. The national territory includes over 44 million ha with various levels of hydric suitability (Figure 1b). Territory that qualifies as without restriction equates to 39.2% of the total hectares, with some level of suitability, while the mild restriction territory makes up 44.8%, and the moderate restriction territory accounts for 16.1%. Territory without restriction is concentrated in the Aysén region, which holds 59.3% of the total land without restriction, followed by the Magallanes and Los Lagos regions, which account for 23.6% and 13.9% of the total land. However, the Los Ríos and Los Lagos regions hold all regional surfaces with some degree of suitability for camelina adoption. The Coquimbo region only presents soils with moderately restricted suitability, equating to 9.2% of the regional surface area.

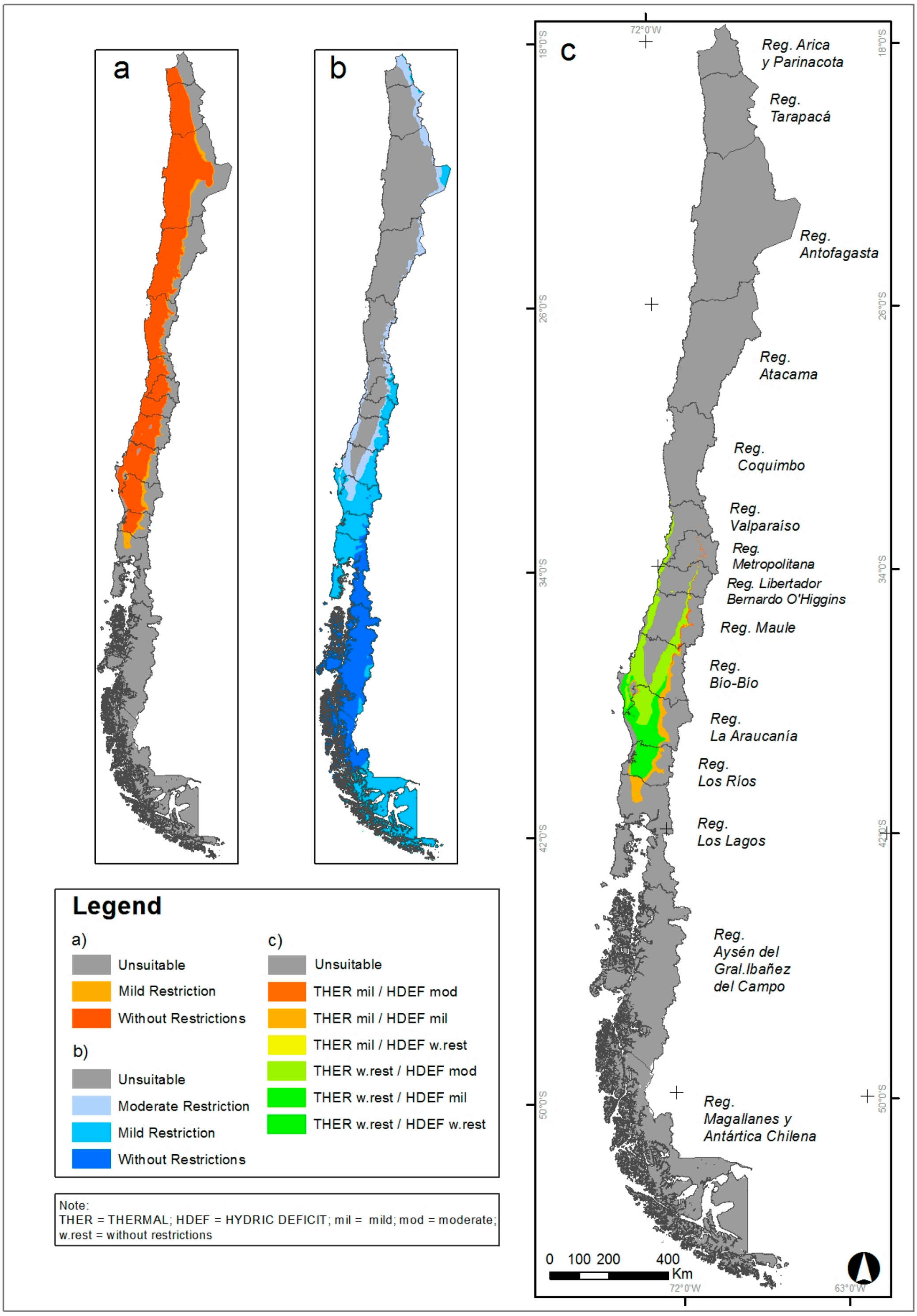

Figure 1. Suitability zoning for camelina in Chile: (**a**) thermic; (**b**) water; and (**c**) climatic.

3.4. Edaphic Factors

Examples of camelina presence and production were found in 15 locations, four of which correspond to the same soil type (Typic Haploxerands), and the registered production of each location was averaged [5,15–17]. The Typic Dystrandepts and Humic Haploxerand [5,16] soil types were considered as Humic Andosol for our purposes, and Xeric Haplocambids [15,17] was considered as Cambisol, grouping all similar soil types in Chile. Finally, 15 locations and 11 soil types were used for soil zoning (Table 3). Suitability levels were determined according to the yield obtained from each of the soils, where soils without a known history were considered in the without information category (Table 4).

Table 3. Cities or towns where camelina is present, which were used to determine the soil requirements for its development.

Country	City/Town	Soil Type		References
		Publication	FAO	
Chile	El Carmen	Typic Haploxerand	Vitric Andosol	[5,16]
Chile	Los Ángeles	Typic Haploxerand	Vitric Andosol	[5,16]
Chile	Osorno	Typic Haploxerand	Vitric Andosol	[5,16]
Chile	Gorbea	Typic Dystrandepts	Humic Andosol	[5,16]
Chile	Chillán	Humic Haploxerand	Humic Andosol	[5,16]
United States	Maricopa	Typic Natrargids	Orthic Solonetz	[11,34]
United States	Morris	Calcic Hapludolls	Calcic Chernozem	[13]
United States	Pendleton	Typic Haploxerand	Vitric Andosol	[15,17]
United States	Lind	Xeric Haplocambids	Cambisol *	[15,17]
United States	Moscow-Pullman	Ultic Haploxerolls	Haplic Kastanozem	[15,17]
United States	Corvalis	Ultic Argixerolls	Luvic Phaeozem	[15,17]
United States	Sheridan	Ustic Haplargids	Luvic Xerosol	[32]
United States	Kalispell	Typic Haplustolls	Haplic Chernozem	[35]
United States	Huntley	Aridic Haplustalfs	Chromic Luvisol	[35]
United States	Mocasin	Typic Calciustolls	Calcaric Phaeozem	[36]

* No specific information was found on the corresponding type of Cambisol, so the entire group was considered.

Table 4. Soil suitability level for camelina adaptation in Chile.

Soil	Without restriction	Chromic Luvisol–Haplic Kastanozem
	Mild restriction	Haplic Chernozem–Luvic Phaeozem–Vitric Andosol
	Moderate restriction	Humic Andosol–Orthic Solonetz–Calcic Chernozem–Cambisol–Calcaric Phaeozem–Luvic Xerosol
	Without information	All remaining soil types
	Restriction	Glaciars (Gelisoles o Criosoles)

Little information exists about soils where camelina is grown; therefore, it was not possible to evaluate territory suitability for its production, and a large portion of the national soils were classified as without information (Table 4). Chromic Luvisol and Haplic Kastanozem were considered to be the best soils for camelina development, as the average production in these cases was 2049 kg·ha^{-1} [34] and 1913 kg·ha^{-1} [15,17], respectively.

3.5. Soil Zoning

Soil zoning determined that over 13 million ha exist in Chile with different levels of adaptability, while there are over 57 million ha of soils without information (Figure 2). The soils without restriction are equal to 31.5% of the total soils with some degree of suitability, while soils with mild restriction are most relevant at the national level, accounting for 68.4% of the total soils with some degree of suitability. The Coquimbo region presented the largest amount of soil without restrictions, with 34.9%, followed by the Valparaíso (17.8%) and Maule (15.6%) regions. Moderate restriction soils were found only in the Tarapaca region, equaling 0.02% of the total soils with some degree of suitability. The Atacama region was not found to have soils with any degree of suitability for camelina establishment.

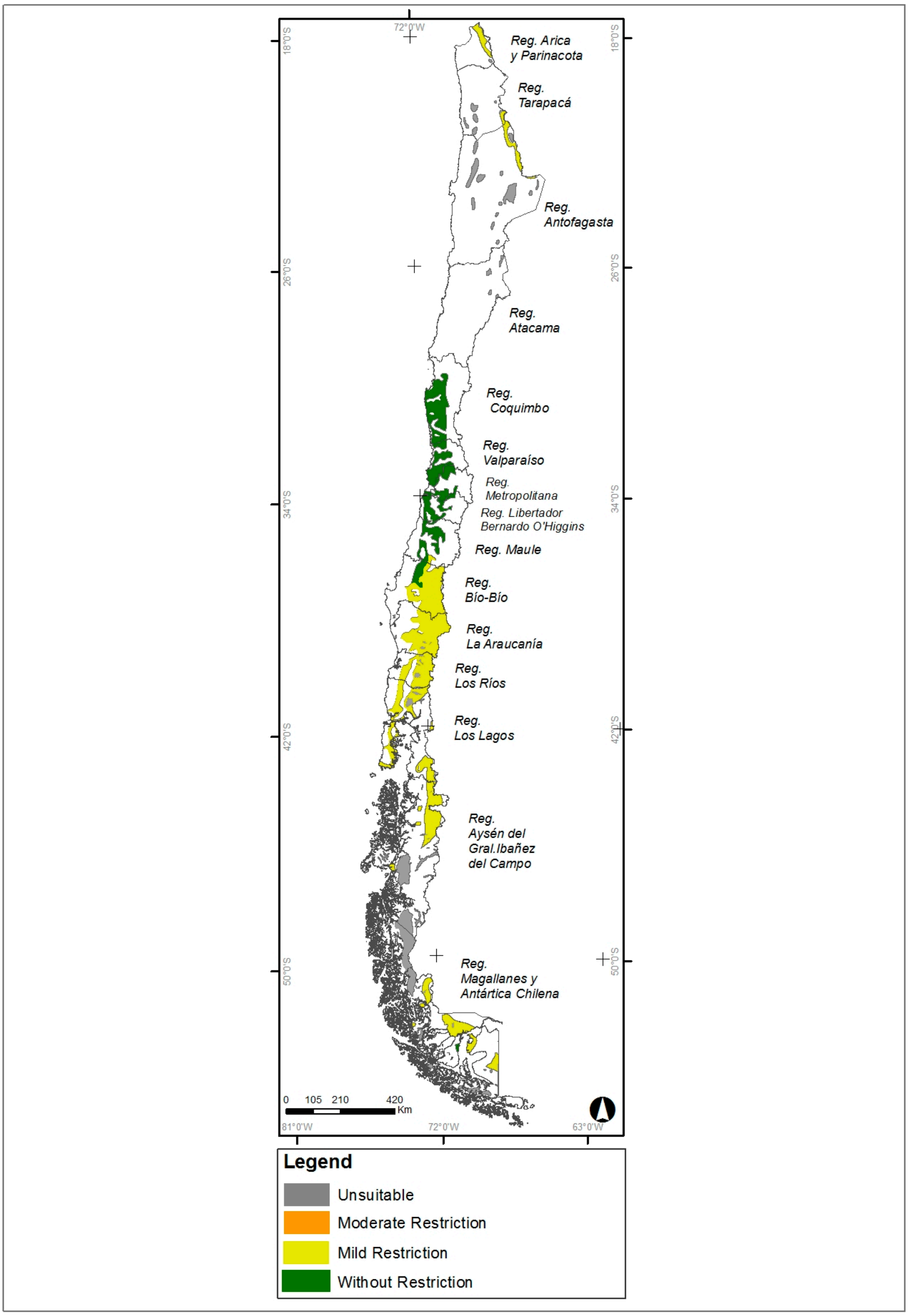

Figure 2. Soil suitability zoning for camelina in Chile.

3.6. Limitations

Variables that act as limitations for camelina cultivation were considered for agro-ecological zoning, and the use of limiting did not correspond to the usual method for zoning. Usually zoning considers only climatic information [37,38]. Current land use, geomorphology, and altitude were considered as limitations (Table 5). It was determined that 61.1% the national territory is suitable given that it has no altitude limitations (Figure 3a). The regions in the extreme north have the greatest altitude restrictions, where 30.6% of the combined surface area of Tarapacá, Arica and Parinacota, Antofagasta, and Atacama showed aptitude for producing camelina, while the Antofagasta region is the most restricted, with 86.1% being unusable. The opposite occurred in the southern regions of Magallanes and Los Ríos, where 90% of the regional surface can be used for camelina production.

Table 5. Limiting variables for camelina adaptation in Chile.

Soil Uses	Unsuitable	Urban Areas–Forests–Wetlands–Bodies of Water–Snow and Glaciers–SNASPE–Agricultural Terrain
	Suitable	Grasslands and Shrublands–Areas without vegetation–Areas without information
Geomorphology	Unsuitable	Mountainous terrain–Steep slopes
	Suitable	Flat terrain–Mildly inclined
Altitude	Unsuitable	>1200
	Suitable	<1200

Geomorphology limitations determined that 43.8% of the national territory can be used for camelina production (Figure 3b). In contrast to the altitude results, the Antofagasta region has the greatest possibility for camelina adoption, as 67.9% of the regional surface area is usable for cultivation. Conversely, the Coquimbo region has the lowest possibility for camelina adoption, as only 22.2% of its surface area allows for camelina production.

Current land use was the greatest limiting factor for camelina cultivation in Chile, where 25.7% of the total national land allows for the introduction of camelina (Figure 3c). The Coquimbo region has the fewest land use limitations, as 76.5% of the surface is available for camelina introduction. In the Aysén region, only 10.7% of its surface showed potential for camelina introduction, and it has the lowest total amount of available land.

The combination of limitations under consideration for camelina zoning determined that 9.21% of national land can host camelina as a crop. The Magallanes region has the greatest amount of land for camelina development, and represents 35.8% of the suitable surface area, as opposed to the Antofagasta region, where only 0.004% of the territory allows for camelina (Figure 3d).

3.7. *Agro-Ecological Zoning*

Suitable lands for camelina, after agro-ecological zoning, were concentrated between the Coquimbo and Los Lagos regions. The furthest regions did not show suitability for camelina due to water limitations in the extreme north (between Arica and Parinacota, and Atacama) and for thermic reasons in the extreme south (Aysén and Magallanes regions) (Figure 4).

At the country level, 1.3% of the national territory showed some level of suitability for camelina adaptation as a productive alternative. The Los Ríos region had the greatest camelina production potential, as 21.4% of the regional surface showed some level of suitability, followed by the Araucanía and Los Lagos regions, with 7.3% and 5.1%, respectively, in relation to the total regional surface (Figure 4; Table 6). In the Los Ríos and Los Lagos regions, lands without restriction and with mild restriction were found for all of the variables studied (thermic, water, and soil) except for 3 ha with moderate water restrictions in the Los Ríos region (Table 6), which is negligible, as it corresponds to less than 0.001% of the suitable land area.

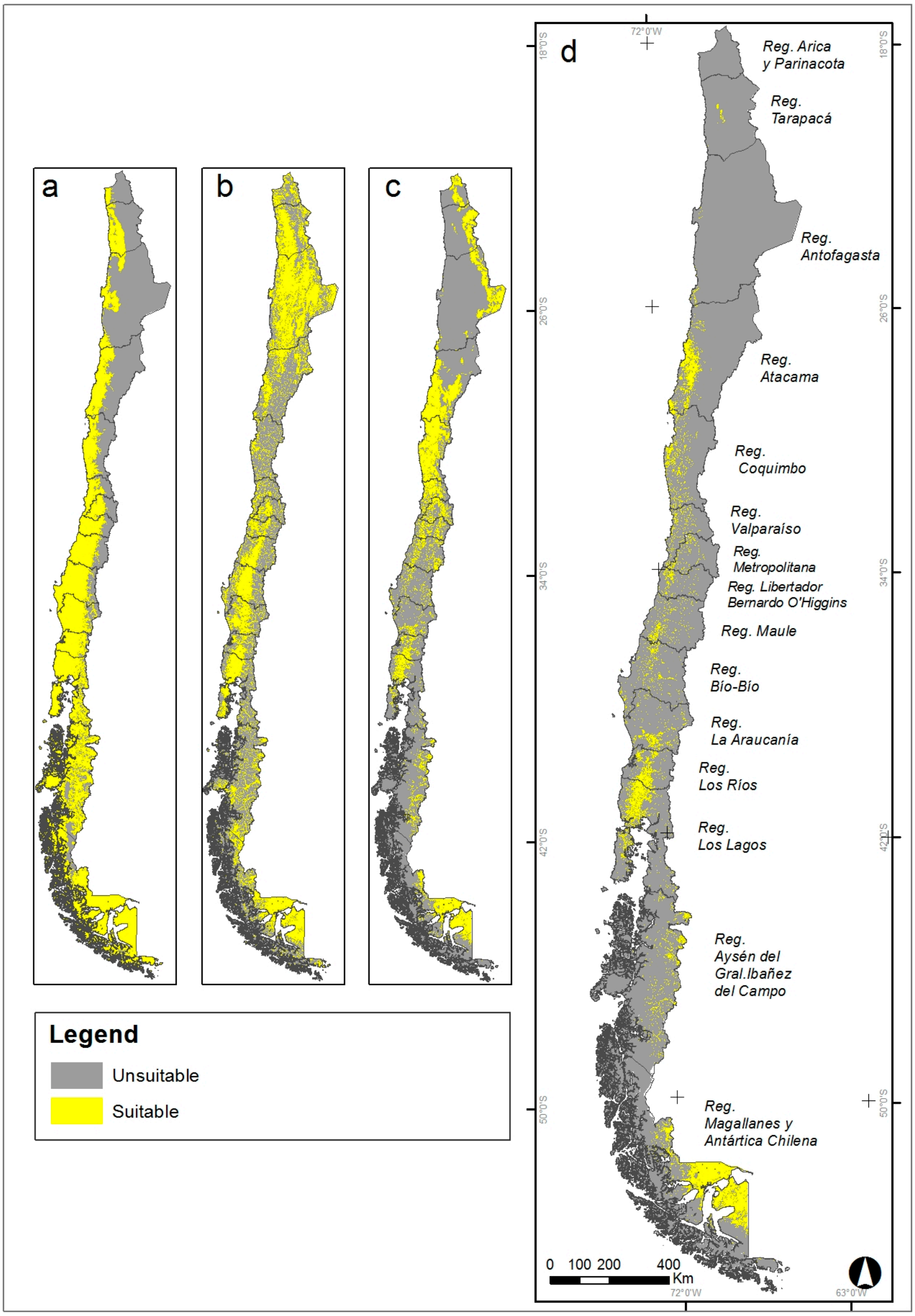

Figure 3. Territory considered to be a limitation for camelina adoption: (**a**) altitude; (**b**) geomorphology; (**c**) current land use; and (**d**) synthesis of limitations, considering altitude, geomorphology, and current land use.

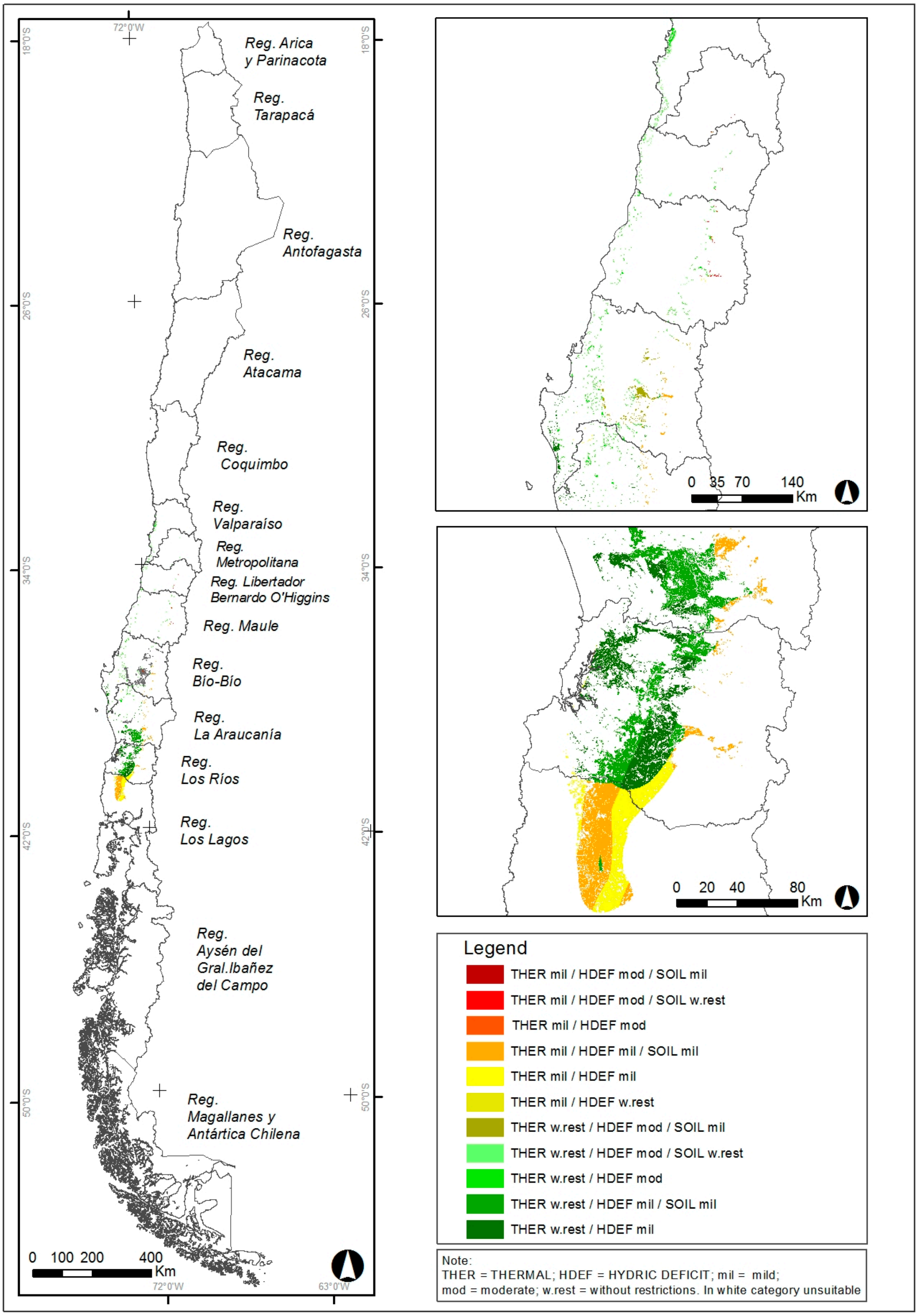

Figure 4. Agro-climatic zoning for camelina in Chile.

Table 6. Regional surface area with adaptation potential for camelina as a national oilseed crop (ha).

Region	1	2	3	4	5	6	7	8	9	10	11	Total
Coquimbo	0	0	0	0	0	0	0	0	1668	0	0	1668
Valparaíso	0	0	0	0	0	0	0	10,791	15,675	0	0	26,466
Metropolitana	0	508	39	0	0	0	0	638	14	0	0	1199
O'Higgins	0	167	749	0	0	0	0	4703	4597	0	0	10,216
Maule	14	0	4402	0	621	0	186	1993	19,233	0	0	26,448
Biobío	97	0	15	11,222	314	0	42,103	2343	40,293	1977	22,585	120,950
Araucanía	0	0	0	27,869	921	0	1559	0	19,371	120,295	47,020	217,036
Los Ríos	0	0	0	13,064	34,693	3	0	0	0	103,100	170,315	321,176
Los Lagos	0	0	0	134,844	94,753	0	0	0	0	5397	513	235,507
Total	111	676	5205	186,999	131,302	3	43,848	20,467	100,851	230,769	240,434	960,664

1: Thermic-Mild Restriction/Hydric-Moderate Restriction/Soil-Mild Restriction; 2: Thermic-Mild Restriction/Hydric-Moderate Restriction/Soil-Moderate Restriction; 3: Thermic-Mild Restriction/Hydric-Moderate Restriction/Soil-Without Information; 4: Thermic-Mild Restriction/Hydric-Minor Restriction/Soil-Mild Restriction; 5: Thermic-Mild Restriction/Hydric-Mild Restriction/Soil-Without Information; 6: Thermic-Mild Restriction/Hydric-Without Restriction/Soil-Without Information; 7: Thermic-Without Restriction/Hydric-Moderate Restriction/Soil-Mild Restriction; 8: Thermic-Without Restriction/Hydric-Moderate Restriction/Soil-Without Restriction; 9: Thermic-Without Restriction/Hydric-Moderate Restriction/Soil-Without Information; 10: Thermic-Without Restriction/Hydric-Mild Restriction/Soil-Mild Restriction; 11: Thermic-Without Restriction/Hydric-Mild Restriction/Soil-Without Information.

4. Discussion

In Chile, Santibañez et al. [37] determined bioclimatic adaptability for moringa (*Moringa oleifera* Lam.); they used the minimum and maximum temperature, degree days and days with frost. Zoning was carried out through bioclimatic analogies, where the conditions among locations from South Africa and Kenya were different with bioclimatic conditions of the country, reducing potential areas.

Falasca et al. [38] carried out a climate zoning for camelina in Argentine territory. They used annual precipitation, precipitation during the productive period (August–December) and average temperatures during periods of vegetative and reproductive growth as factors in evaluating camelina suitability. The use of variables relevant for camelina production seasons permit greater specificity regarding land suitability; however, it is also necessary to consider variety in use, especially if there are certain cultivars for different seasons [7,13,15] in which case variable ranges must be considered according to the cultivar in use. The present work considers generic ranges for the selected variables, where information was used for existing cultivars. It is a first approximation for camelina production in Chile, which can be used as a tool to support decision-making and to evaluate the species' introduction as a raw material for biodiesel production or other industrial products.

The present work considered the entire productive period for degree day calculation, which in Chile was 221 days for spring cultivars [5]. Gesch [14] determined productive cycles that oscillate between 75 and 100 days between sowing and harvest for spring cultivars sown in Morris, Minnesota, in the north central United States. Gesch and Cermak [13] used winter cultivars, also in Morris, Minnesota, but had a productive cycle around 226 days between sowing and blooming.

It was determined that, with a water deficit greater than 500 mm annually, the area was considered to be restricted during water zoning (Table 2). This is manageable, because there are irrigation alternatives that must be developed for industrial crops, especially regarding biofuel production. In the north of Chile, where water and agriculturally viable soil are scarce [18], use of treated wastewater could be an effective option to habilitate territory for non-food crops [39]. Only one [11] of the 27 locations considered in this study has an arid climate. French et al. [11] evaluated camelina production in Maricopa, Arizona, United States, where they found productivity of up to 1500 kg·ha^{-1}, with approximately 2900 degree days. This way, applying irrigation for camelina production in arid climates can be an alternative, for which future studies can evaluate the possibility of growing camelina in the northern territory of Chile using irrigation with treated wastewater.

Soil zoning in Chile is complicated, due to the scarcity of existing information. Soil type data was only obtainable from Chile and the United States, and even then, only for 11 types of soils. In addition, not all of these soils are registered in the country, so a large part of the national territory is categorized as without information during soil zoning (Figure 2). Information on soil resources is still insufficient for accurate zoning. Soil type and quality are relevant parameters for agricultural production, since crops depend on these factors to develop favorably [40].

The agro-ecological zoning results obtained are in accordance with those published by Berti et al. [5] and Solis et al. [16], who conducted studies between the Biobío and Los Lagos regions, and determined that south central Chile possesses adequate conditions for camelina production. These precise regions possess the most land surface area for camelina production. The Biobío, Araucanía, Los Ríos and Los Lagos regions hold 93.1% of suitable lands, where 49.0% of land is without thermic restriction, mild water restriction, and mild soil restriction or without information (Table 6).

5. Conclusions

Considering the available soil and climate information for camelina production for biodiesel, it is concluded that the Araucanía, Los Ríos and Los Lagos regions present the greatest potential for camelina adoption. These regions together possess 80.5% of the national territory with potential for camelina production. The Los Ríos region, as well as the Araucanía region to a lesser extent, showed the greatest suitability (without thermic restriction, mild water restriction, soil with mild restriction or without information) at a national level. Camelina can be an interesting alternative for non-agricultural soils in Chile, especially considering that studies have already been conducted, with successful results regarding productivity.

The model and agro-climatic ranges used in this study could be replicated in other countries, especially because there is information from different locations where camelina grows. Additionally, the accuracy of agro-climatic ranges can be improved according to newly published papers or information regarding the grow and yield of camelina in other locations.

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