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Article

A Comparison of Two Methodological Approaches for Determining Castor Bean Suitability in Chile

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Abstract: Castor bean (*Ricinus communis* L.) contains ricinoleic acid, making it one of the world's most important oil-seeds. There are few studies on this species in Chile, despite its potential as an industrial crop. This study evaluated two methodologies (simplistic and presence-species) for determining the aptitude of land for growing castor beans, both of which use climatic information. The simplistic and presence-species methodologies identified 27.89 and 13.19 million ha, respectively. The most important difference between both methodologies was that the mean minimum annual temperature (TNA) was −8.0 °C in the simplistic method, meaning that some areas in the southernmost regions of Chile (Aysén and Magallanes) should be able to grow the plant. Therefore, TNA = 8.0 °C was selected, and the zonation by simplistic methodology was updated. Consequently, both zonations showed similar results, although the presence-species method included northern coastlines, precisely where castor bean has been recorded, while the simplistic method did not. Finally, both methodologies determined the best condition to be central-south Chile, between the Maule and Araucanía regions, even though castor bean presence has only been recorded up to the Maule region. These regions have a huge potential to establish castor beans, but more information about agronomic practices is necessary for its development in Chile.

Keywords: industrial crops; marginal land; agro–climatic zonation; land suitability; biodiesel

1. Introduction

Castor bean (*Ricinus communis* L.) is extensively distributed in tropical conditions, even though it has also been introduced under subtropical conditions [1]. This plant has a perennial behavior in nature, but can sometimes be treated as an annual crop when cultivated, especially in semi-arid and arid conditions [2]. In Chile, its presence has been registered between the Arica y Parinacota and Maule regions [3]. Further, it has recently been reported that the oil content in Chilean castor bean accessions ranged from 45.7 to 54.0% and that it was greater than 50% in seven Chilean accessions [3]. Despite what is already known, there is little information about castor bean in the country, especially from an agronomic viewpoint.

On the other hand, it is a very important industrial crop due to its unique nonedible seed-oil [4,5] and the fact that it can grow in marginal land, where crops for food and feed production usually grow poorly [5]. Castor bean seeds contain 28–59% seed-oil, and ricinoleic acid (12-hydroxy-9-cis-octadecenoic acid) is its most abundant fatty acid (79–92%) [6,7]. Castor oil production reaches 1.8 million tons annually; India, China, and Brazil are its largest producers, while the USA, Japan, and EU countries are its largest importers [8].

Ricinoleic acid is important because it is used to create many products of interest and has the potential to be chemically transformed due to the presence of the hydroxyl group (-OH) in its 12-carbon and a double bond between 9th and 10th carbons [9,10]. For this, castor oil can be employed for agriculture, pharmaceuticals, energy, cosmetics, medicine, and others, making it a very valuable seed-oil [10,11]. Despite its potential, worldwide production varies constantly, and its demand sometimes exceeds its supply [8,9]. Moreover, there are other oil-seeds more releva nt for oil production in the world, e.g., palm, soybean, rapeseed, or sunflower oil—even for energy purposes [12].

Among oil-seeds available in the international market, castor bean is one of the few plants with the potential to grow in drought conditions and marginal land [1,13]; it is considered a second-generation raw material, i.e., it does not compete with food or feed production [14]. In addition, its adaptation and productive potential under Mediterranean conditions have also been studied, though these studies have mainly focused on oil production in adventitious germplasm without evaluating agronomic practices [15–17].

There are two cultivars—"Hale" and "Brigham"—that can grow under semi-arid or arid conditions [18,19]. The Hale and Brigham cultivars were evaluated in Texas, USA, and their seed productivity reached around 2000 to 2500 kg seed ha^{-1} [18,19], and the seed-oil production for Hale cv was 45.3–47.8% [18]. Under Mediterranean conditions, Zanetti et al. [4] evaluated four hybrid cultivars in Bologna, Italy, and Aliartos, Greece. The seed productivity reached around to 2200 kg seed ha^{-1} in Greece and 1600 kg seed ha^{-1} in Italy, with an oil content of 50 and 55%, respectively [4]. They concluded that castor bean has the potential to grow in both places, although castor bean in Aliartos, Greece, would require irrigation, whereas in Bologna, Italy, it only needs rainwater [4]. Moreover, four castor bean wildtype accessions evaluated in Sicily, Italy, showed unequal results, even though a Tunisian accession reached around 5700 kg seed ha^{-1} and 44.7% seed-oil without irrigation, with peak production in the second year [15].

There is little information about castor bean adaptation under semi-arid conditions in a Mediterranean climate. Ecological niche modeling allows us to determine the potential distribution of species using biotic or abiotic information [20]. However, for agronomic purposes, the potential distribution of a particular species must be complemented with territorial information [21,22]. Actually, land suitability assessments evaluate land for different purposes employing tools about land and crop management so that decision makers can optimize crop production [21]. Moreover, because competing land uses are considered as limitations for crop establishment, land suitability assessments can also be useful for avoiding environmental conflicts [22].

In line with this, Falasca et al. [23] developed a simplistic method based on the standard climatic values of adaptation to evaluate castor bean land aptitude under semi-arid and arid conditions. They made a bibliographic review for determining climatic aptitude and determined the standard values directly from every publication queried. They applied their zonation model in Argentina and finally concluded that the model generated can be applied in any country employing the agro–climatic limits that they obtained [23].

Román-Figueroa et al. [24], on the other hand, developed a methodology based on species presence to evaluate the most suitable land for energy or industrial crops using niche modeling; their bibliographic review found places in which that species was registered as being productive in nature. Climatic information was obtained for each place, and climatic ranges were selected to determine land suitability.

Using the background information presented above, the present study determined the Chilean territory potential for castor bean adaptation, considering both simplistic and presence-species methodologies. Thus, we determined castor bean's climate requirements and how suitable existing territory in Chile is to grow it.

2. Materials and Methods

2.1. Materials

Climatic maps were obtained from the Bioclimatic Atlas of Chile [25]. The protected wilderness areas, land currently in use, and other data were obtained from the Chilean Ministry of the Environment [26].

2.2. Determining Land Aptitude for Castor Bean with the Simplistic Method

The simplistic methodology developed by Falasca et al. [23] was used as the first approximation for land determination in Chile on which the castor bean plant can be grown. They did an international bibliographic review to determine the climatological requirements of castor plants. This methodology determined climatic parameters (precipitation, temperature, and frost-free season) directly and used the information to select agro–climatic zones. Average annual temperature (TX) and annual precipitation (Pp) were considered factors and found to be 15 °C to 27 °C, and 250 mm, respectively. Moreover, they employed mean minimum annual temperature (TNA; −8.0 °C) and frost-free season (FFD; 180 days) to be limiting. Eleven agro–climatic zones were classified as optimal, very suitable, suitable, marginal, or not suitable (Table 1).

Table 1. Parameters for determining agro–climatic zones, according to the simplistic methodology of Falasca et al. [23].

Aptitude	Pp	TX	TNA	FFD
Optimal	>750 mm	24.0–27.0 °C	>−8.0 °C	>180 days
Very suitable	>750 mm	21.0–23.9 °C	>−8.0 °C	>180 days
Suitable with humid regime	>750 mm	16.0–20.9 °C	>−8.0 °C	>180 days
Suitable 1 with subhumid regime	450–750 mm	24.0–27.0 °C	>−8.0 °C	>180 days
Suitable 2 with subhumid regime	450–750 mm	21.0–23.9 °C	>−8.0 °C	>180 days
Suitable 3 with subhumid regime	450–750 mm	16.0–20.9 °C	>−8.0 °C	>180 days
Marginal due to humidity	200–450 mm	-	-	-
Marginal due to temperature	-	<16.0 °C	-	-
Marginal due to frost 1	-	-	-	<180 days
Marginal due to frost 2	-	-	<−8.0 °C	-
Not suitable	<200 mm	<16.0 °C	<−8.0 °C	<180 days

Pp: Annual precipitation; TX: Average annual temperature; TNA: Average minimum annual temperature; FFD: Free-frost day.

2.3. Determining Land Aptitude for Castor Bean with the Presence-Species Method

The presence-species methodology, developed by Román-Figueroa et al. [24], was employed as a second approximation for determining castor bean plant suitability in Chile. Briefly, an international bibliographic review was made to determine places where castor bean plants grow, and geographic coordinates and climatic information were registered. Monthly average minimum temperature (°C), monthly average maximum temperature (°C), relative average monthly humidity (%), and monthly precipitation (mm) were considered and registered. Moreover, water-deficit (WD), degree days (DD), and potential evapotranspiration (ETp) were calculated as derived variables. More details on how WD, DD, and ETp were determined in the presence-species methodology can be found in recent literature [24] and [27].

Adaptable ranges for castor bean were subsequently determined for each climatic variable by scatterplots between the variables. Hydric zoning used WD because it includes precipitation and ETp, whereas thermal zoning considered maximum temperature of the warmest month (TMX), minimum temperature of the coldest month (TNJ), and DD variables.

Finally, climatic zoning was determined according to the land evaluation theory of Rossiter [28], where land suitability is obtained from land characteristics and crop requirements; thus, land is evaluated according to qualitative or quantitative approach [21,22,28]. Land suitability, at the national level, was determined through a qualitative approach, selecting factors associated with the climatic requirements of castor bean and their respective aptitude levels. Climatic factors were categorized according to the following levels of restriction: without restriction, mild restriction, moderate restriction, and restricted. The information was processed using ArcGIS® 10 (Esri, Redland, CA, USA, http://www.esri.com/software/arcgis) and the method of decision rules using Boolean operators based on top-down logic.

Both simplistic and presence-species zonation methodologies were complemented with current land uses for the determination of limitations in land aptitude for castor bean growth, according to agro–climatic zonation methodology [28]. Limitations keep restriction levels of climatic factors or remove the land aptitude for crop establishment [27]. Urban areas, forests, wetlands, water bodies, snow, and glaciers, protected wildlife areas, and agricultural lands were considered as limitations removing the land aptitude in those uses.

3. Results

3.1. Land Aptitude Determination Using the Simplistic Method

Chile has a total surface area of 75.29 million ha. From climatic-zonation using the simplistic methodology, it was found that 27.89 million ha (37.04% of the country's area) has some level of aptitude for castor bean growth (Figure 1A). This area is localized between the Coquimbo and Magallanes regions, excluding the northernmost regions of Chile. Therefore, 37.04% of the national territory is suitable for growing castor bean. The southernmost regions of Chile have the greatest area that is suitable—23.65%, 14.91%, and 14.82% of the total surface area with aptitude registered in the Magallanes, Los Lagos, and Aysén regions, respectively—but the aptitude level in these regions was marginal due to temperature (4 in Table 2). The Los Ríos region had the greatest area with aptitude—93.34% of the Los Ríos region's total territory—according to the regional surface, although all land with aptitude was marginal due to temperature (Table 2).

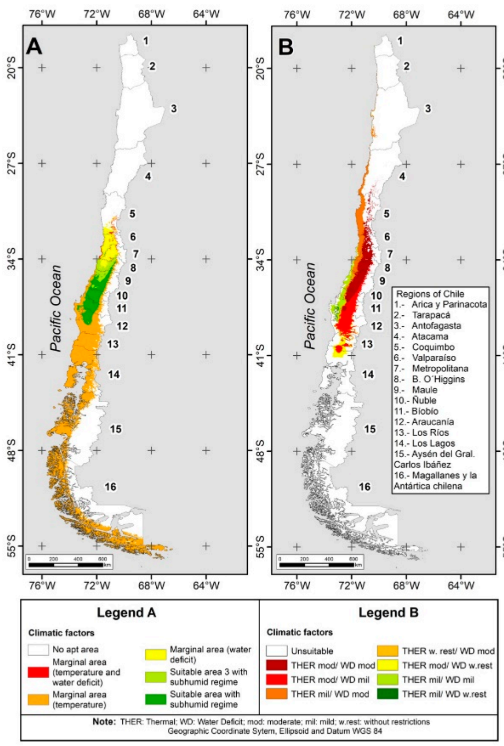

Figure 1. Suitability zoning for castor bean in Chile according to the simplistic method (**A**) and presence-species method (**B**). Therm: Thermic; WD: Water deficit; mod: Moderate: mil: Mild; w. rest: Without restriction.

Table 2. Regional surface area with climatic aptitude for castor bean production as a national oil-seed crop (ha), according to the simplistic methodology. Chilean total area: 75.29 million ha.

	1	2	3	4	5	6	7
Coquimbo	0	0	403,326	0	0	101,011	0
Valparaíso	0	45,978	971,754	28,362	0	138,275	0
Metropolitana	0	94,182	750,915	59,224	0	28,590	0
O'Higgins	106,118	671,834	281,609	154,878	0	132	0
Maule	1,120,793	548,328	0	425,180	0	0	0
Ñuble	842,597	19	0	204,494	0	0	0
Biobío	959,325	0	0	902,283	0	0	0
Araucanía	719,689	0	0	1,731,779	0	0	0
Los Ríos	0	0	0	1,712,376	0	0	0
Los Lagos	0	0	0	4,157,466	0	0	0
Aysén	0	0	0	4,133,116	0	0	0
Magallanes	0	0	0	6,594,879	0	0	0
Total	3,748,521	1,360,341	2,407,603	20,104,037	0	268,009	0

1: Suitable land with a humid regime; 2: Suitable area 3 with a subhumid regime; 3: Marginal area (water deficit); 4: Marginal area (temperature); 5: Marginal area (frost); 6: Marginal area (temperature and water deficit); 7: Marginal area (water deficit and frost).

There was 20.1 million ha of suitable land that was marginal due to temperature, i.e., 72.09% of the total land with some aptitude (Table 2). On the other hand, there were 3.75 million ha (13.44%) of suitable land with a humid regime (1 in Table 2), and it was concentrated between the O'Higgins and Aracaunía regions (Figure 1A). This category included the best conditions according to this zonation method because optimal and very suitable aptitude were not registered in Chile. In addition, no land with frost restriction was registered in Chile (5 and 7 in Table 2).

3.2. Land Aptitude Determination using the Presence-Species Method

There were 47 places where castor bean presence was registered and climatic information was available (Table A1). Climatic information (thermal and hydric) was obtained for each place. This information was used to establish the aptitude ranges in which castor bean can grow (Table 3).

Table 3. Thermal and hydric critical ranges for castor bean adoption in Chile.

Parameters	Aptitude	Ranges
TMX (°C)	Restricted	>33; <22
	Mild Restriction	30–33; 22–25
	Without Restriction	25–30
TNJ (°C)	Restricted	<1
	Moderate Restriction	1–5
	Mild Restriction	5–9
	Without Restriction	>9
DD	Restricted	<700
	Moderate Restriction	700–1000
	Mild Restriction	1000–1300
	Without Restriction	>1300
WD (mm)	Restricted	>−1250
	Moderate Restriction	−1250–750
	Mild Restriction	−750–250
	Without Restriction	<−250

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

Climatic-zonation found that 13.19 million ha in Chile (17.52% of the country's area) had some aptitude for castor bean production (Figure 1B). There was no ideal area for castor bean production in Chile, as all areas had some thermic and hydric restrictions (Figure 1B; Table 4). The Maule, Araucanía, and Coquimbo regions had the highest land concentration with some aptitude level, with 14.70%, 14.69%, and 13.87%, respectively, of the total land having climatic aptitude. However, the aptitude level was different in each of these regions. Coquimbo mainly included land with mild thermic and moderate hydric restrictions (10 in Table 4). In contrast, in the Maule region, the majority of land had moderate thermic and hydric restrictions (8 in Table 4), while that in the Araucanía regions had moderate thermic and mild hydric restrictions (9 in Table 4).

Table 4. Regional surface area with climatic aptitude for castor bean production as a national oil-seed crop (ha), according to the presence-species methodology. Chilean total area: 75.29 million ha.

	8	**9**	**10**	**11**	**12**	**13**	**14**
Arica y Parinacota	0	0	2880	5852	0	0	0
Tarapacá	0	0	37,496	1695	0	0	0
Antofagasta	78	0	206,719	69,960	0	0	0
Atacama	45,458	0	445,319	2561	0	0	0
Coquimbo	473,229	0	1,347,439	9246	0	0	0
Valparaíso	449,427	145	507,965	0	0	81,794	0
Metropolitana	719,943	0	152,611	0	0	2018	0
O'Higgins	699,949	52,015	288,784	0	0	120,607	0
Maule	1,136,464	223,448	201,948	0	0	376,449	0
Ñuble	427,724	309,153	40,476	0	0	180,285	0
Biobío	115,345	579,346	2451	0	16,634	542,048	64,766
Araucanía	14,377	1,507,694	0	0	205,329	151,861	57,820
Los Ríos	0	331,598	0	0	450,471	0	0
Los Lagos	0	120,761	0	0	409,508	0	0
TOTAL	4,081,993	3,124,160	3,234,087	89,315	1,081,942	1,455,063	122,586

8: Moderate thermic and hydric restriction; 9: Moderate thermic restriction and mild hydric restriction; 10: Mild thermic restriction and Moderate hydric restriction; 11: Without thermic restriction and Moderate hydric restriction; 12: Moderate thermic restriction and without hydric restriction; 13: Mild thermic and hydric restriction; 14: Mild thermic restriction and without hydric restriction.

On the other hand, the Biobío and Araucanía regions had the best condition for castor bean production in Chile. Both regions registered 122,586 ha (0.93% of the total land with some aptitude level) with mild thermic restrictions and without hydric restrictions (Table 4). Thirty point nine percent of the total land with some aptitude level had moderate thermic and hydric restrictions, and this was concentrated in the central valley of Chile (Figure 1B).

3.3. Land Aptitude with Current Land Use as Limitations

Land aptitude in agro–climatic zonation, considering current land uses as limitations, found 4.29 and 4.59 million ha with some level aptitude under the simplistic and presence-species methods, respectively (Figure 2; Table 5). The simplistic method showed a reduction of 84.62% in the total land with aptitude in comparison with climatic zonation (Figure 1A; Table 2), while the presence-species method showed a reduction of 65.20% in the total land with aptitude in comparison with climatic zonation (Figure 1B; Table 4).

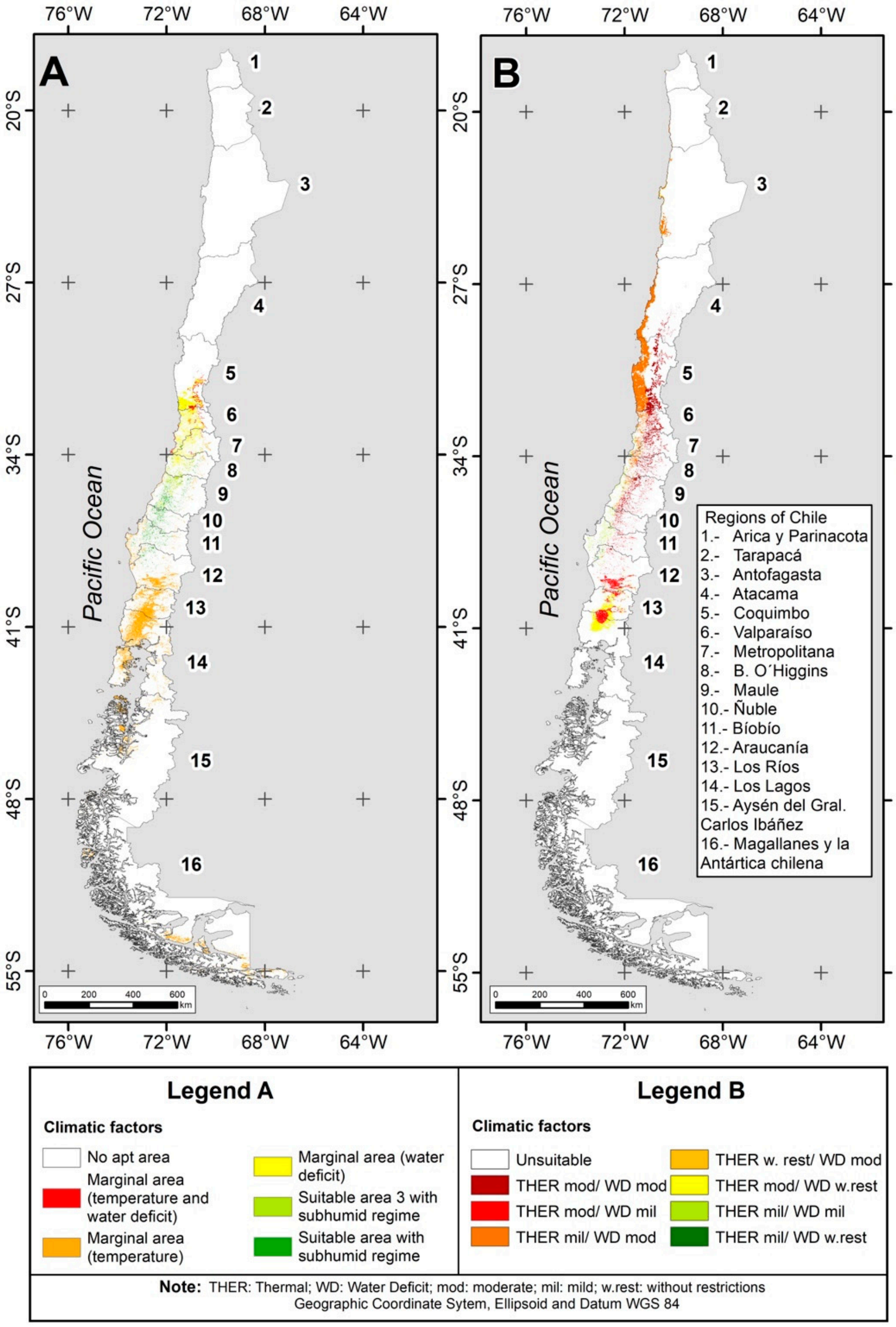

Figure 2. Suitability agro–climatic zoning for castor bean in Chile, according to the simplistic method (**A**) and presence-species method (**B**), considering current land uses as limitations for determination of land aptitude. Therm: Thermic; WD: Water deficit; mod: Moderate; mil: Mild; w. rest: Without restriction.

Land suitable from agro–climatic zonation with the simplistic method was concentrated in the Los Lagos region with 1.01 million ha (23.44% of land with some aptitude level), followed by Los Ríos and Coquimbo regions with 493,132 ha (11.47%) and 460,712 ha (10.72%), respectively (Simplistic methodology in Table 5). A total area of 360,067 ha was registered with the best conditions for castor bean adaptation in the O'Higgins, Maule, Ñuble, Biobío, and Araucanía regions (1 in Table 5).

Land suitable from agro–climatic zonation with the presence-species method was concentrated in the Coquimbo region with 1.61 million ha (35.06% of land with some aptitude level), followed by Atacama and Los Ríos regions with 442,574 ha (9.62%) and 388,190 ha (8.44%), respectively

(Presence-species methodology in Table 5). A total area of 11,851 ha was registered with the best conditions for castor bean adaptation in the Biobío and Araucanía regions (14 in Table 5).

Table 5. Regional surface area with agro–climatic aptitude for castor bean production as a national oil-seed crop (ha), both with the simplistic and the presence-species methodologies. Chilean total area: 75.29 million ha.

Simplistic	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Coquimbo	0	0	361,514	0	0	99,198	0
Valparaíso	0	13,043	312,784	17,092	0	66,064	0
Metropolitana	0	21,343	160,059	28,197	0	9836	0
O'Higgins	9588	90,642	66,841	19,376	0	35	0
Maule	132,037	125,110	0	44,641	0	0	0
Ñuble	83,651	19	0	13,774	0	0	0
Biobío	90,185	0	0	122,105	0	0	0
Araucanía	44,606	0	0	323,168	0	0	0
Los Ríos	0	0	0	493,132	0	0	0
Los Lagos	0	0	0	1,007,641	0	0	0
Aysén	0	0	0	278,154	0	0	0
Magallanes	0	0	0	265,411	0	0	0
Total	360,067	250,157	901,197	2,612,690	0	175,133	0
Presence-species	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Arica y Parinacota	0	0	1137	2989	0	0	0
Tarapacá	0	0	26,143	1663	0	0	0
Antofagasta	72	0	186,000	63,009	0	0	0
Atacama	43,626	0	396,578	2370	0	0	0
Coquimbo	456,160	0	1,147,868	8404	0	0	0
Valparaíso	197,590	144	146,353	0	0	20,059	0
Metropolitana	155,946	0	45,922	0	0	1327	0
O'Higgins	93,155	4526	65,827	0	0	13,825	0
Maule	171,440	16,066	52,796	0	0	44,968	0
Ñuble	50,800	12,592	4648	0	0	21,252	0
Biobío	8058	36,179	144	0	1050	69,435	5136
Araucanía	3121	242,490	0	0	32,935	17,008	6716
Los Ríos	0	174,276	0	0	213,914	0	0
Los Lagos	0	99,447	0	0	234,417	0	0
Aysén	0	0	0	0	0	0	0
Magallanes	0	0	0	0	0	0	0
Total	1,179,968	585,720	2,073,415	78,435	482,316	187,874	11,851

Simplistic methodology. 1: Suitable land with a humid regime; 2: Suitable area 3 with a subhumid regime; 3: Marginal area (water deficit); 4: Marginal area (temperature); 5: Marginal area (frost); 6: Marginal area (temperature and water deficit); 7: Marginal area (water deficit and frost). **Presence-species methodology**. 8: Moderate thermic and hydric restriction; 9: Moderate thermic restriction and mild hydric restriction; 10: Mild thermic restriction and Moderate hydric restriction; 11: Without thermic restriction and Moderate hydric restriction; 12: Moderate thermic restriction and without hydric restriction; 13: Mild thermic and hydric restriction; 14: Mild thermic restriction and without hydric restriction.

4. Discussion

4.1. Land Aptitude with −8.0 °C as TNA

Land that is suitable for castor bean production based on the simplistic methodology reached the southernmost regions of Chile (Aysén and Magallanes regions) (Figures 1A and 2A) because land with frost restriction was not registered (Table 5). These regions have the lowest crop production in the country [29] due to their polar climate [30], with its coldest month reaching as low as −5.0 and 5.0 °C [25]. Land in both regions is mainly used for silvopastoral systems [31] because it is extremely difficult to establish crops there, and, therefore, it would probably be difficult to establish castor bean plants there. The simplistic method applied by Falasca et al. [23] considered an annual mean minimum temperature of −8.0 °C, but there is no castor bean germplasm in Europe that could grow under these conditions. However, castor bean has only been registered in Mediterranean countries, such as Spain [16], Greece [4,5], and Italy [4], the winter minimum temperatures of which are 0.0–10.0 °C in Greece [32] and −3.0–11.0 °C in Spain [33]. It was found that castor bean plants can survive chilling stress, i.e., low non-freezing temperatures [7,34], but there is no information about their behavior below 0.0 °C.

Agro–climatic zoning was determined using the simplistic methodology, and the zonation parameters were changed to make TNA = 8.0 °C (Table 1) according to Patanè et al. [1], who determined that 8.0 °C could be a base temperature for castor bean growth. The southernmost regions, Aysén and Magallanes, did not show land aptitude (Figure 3), in contrast to the original zonation results (Figure 1A); only the coastal zone in the Los Ríos and Los Lagos regions showed some level of aptitude (marginal area by temperature), probably because the sea coast influence acts as a thermic regulator that avoids very low minimum temperatures (frost) and high fluctuations in the daily temperature [35].

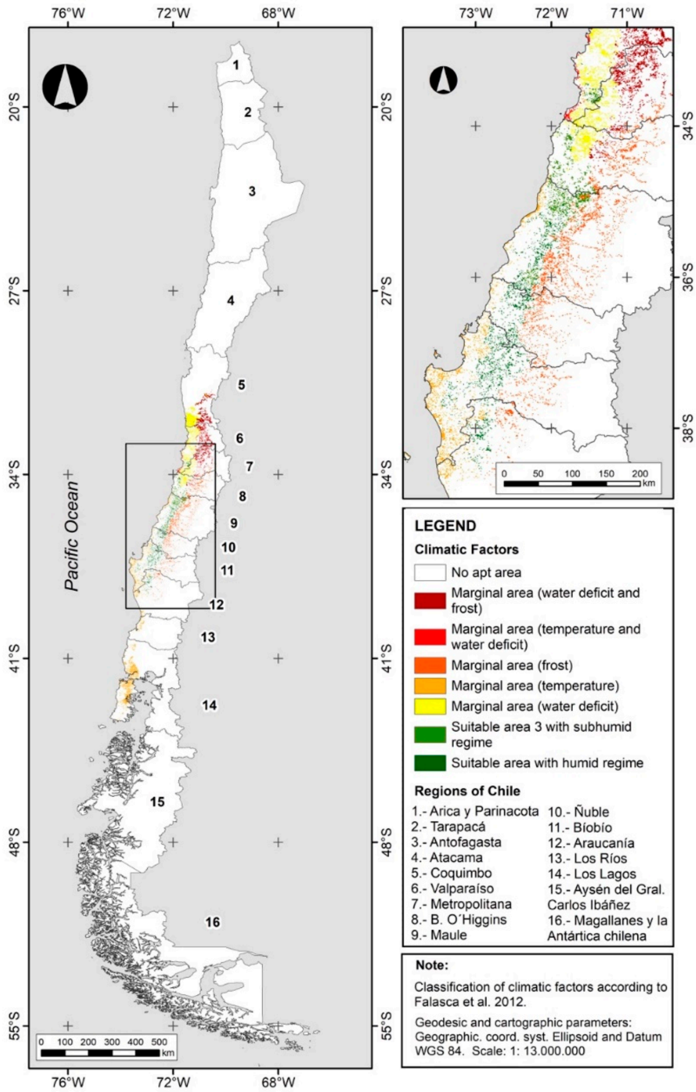

Figure 3. Suitability zoning for castor bean production in Chile according to agro–climatic zonation from the simplistic methodology, but with TNA = 8.0 °C.

Land that was appropriate for castor bean growth decreased by 53.21% when TNA was set to 8.0 °C, decreasing from 4.29 million ha (Simplistic methodology in Table 5) to 2.01 million ha (Table 6). This is mainly because this change excluded the southernmost regions and the inland and highland between the O'Higgins and Los Lagos regions (Figures 1A and 3). The largest change that occurred when the TNA was changed to 8.0 °C was observed on marginal land, where land for castor bean growth decreased in area by 81.51%, from 2.61 million ha to 483,093 ha. An area of 320,419 ha of land was made marginal by frost, and 421,982 ha became marginal by both frost and water deficit (5 and 7 in Table 6), including land registered in the interior valleys between the Coquimbo and Araucanía regions (Figure 3). Frost is one of the most consequential abiotic stresses in Chile, registering economic and productive losses of up to US $354 million [36]. Therefore, castor bean adaptation in Chile must be conditioned for frost occurrence probability, especially because of its tropical origin [7] and that these plants are normally sensitive to cold, i.e., they do not tolerate temperatures under 0 °C [37].

Table 6. Regional surface area with agro–climatic aptitude for castor bean production as a national oil-seed crop (ha), according to a slightly altered simplistic methodology (TNA = 8.0 °C). Chilean total area: 75.29 million ha.

	1	2	3	4	5	6	7
Coquimbo	0	0	207,524	0	0	0	153,989
Valparaíso	0	12,275	165,154	1652	768	17,161	147,629
Metropolitana	0	3096	53,407	0	18,247	0	106,652
O'Higgins	0	41,516	53,129	1457	58,714	25	13,711
Maule	47,906	68,847	0	22,734	140,394	0	0
Ñuble	33,728	19	0	7174	49,923	0	0
Biobío	60,814	0	0	106,448	29,372	0	0
Araucanía	21,605	0	0	37,087	23,002	0	0
Los Ríos	0	0	0	26,743	0	0	0
Los Lagos	0	0	0	279,797	0	0	0
Aysén	0	0	0	0	0	0	0
Magallanes	0	0	0	0	0	0	0
Total	164,052	125,753	479,215	483,093	320,419	17,186	421,982

1: Suitable land with a humid regime; 2: Suitable area 3 with a subhumid regime; 3: Marginal area (water deficit); 4: Marginal area (temperature); 5: Marginal area (frost); 6: Marginal area (temperature and water deficit); 7: Marginal area (water deficit and frost).

4.2. Comparison of the Two Methodologies

Both methodologies found that hydric conditions had a large influence in Chile. Consequently, the coastal zone (determined by the presence-species methodology) was the only area in the northernmost region that showed aptitude (Figure 2B). This can be explained by the low rains that were recorded in these regions, which resulted in 3 to 250 mm year^{-1} between the Arica y Parinacota region and the southern Coquimbo region [23]. On the other hand, the only hydric parameter that the simplistic methodology considered was precipitation, while the presence-species methodology considered WD, that included ETp and Pp. The WD is lower along the Chilean coast than inland due to the marine influence [25].

Furthermore, the land with the best conditions based on the presence-species methodology was between the Biobío and Araucanía regions (Figure 2B), whereas, according to the simplistic methodology, that was between the Maule and Araucanía regions (Figure 3). Therefore, both methods determined similar conditions as the best for castor bean adaptation. Castor bean is found as far as the Maule region [3], but it has not been recorded between the Ñuble and Araucanía regions. Therefore, there is an opportunity to establish castor bean in Chile as an industrial crop. However, precautions should be taken when growing castor bean in the best conditions for its establishment because it is not a native species, and, therefore, runs the risk of becoming invasive [38].

Currently, castor bean is registered between the Arica y Parinacota and del Maule regions [3]. Therefore, it could probably grow under mild thermic restrictions and moderate hydric restrictions (Figure 2B) along the coastal line due to the humidity coming from the ocean in the northernmost regions and the fact that castor bean has been recorded in this area [3]. On the other hand, castor bean has also been registered in the Arica y Parinacota region and between the Atacama and O'Higgins regions in the inland area, but it is always associated with a water body or in farmland borders [3,39] (Figure 4).

Figure 4. Wild castor bean (*Ricinus communis* L.) growing near a body of water in San Joaquín, Metropolitana region, Chile. (33°28′50″ S; 70°37′51″ W).

5. Conclusions

The results obtained by the presence-species methodology corresponded well with the actual castor bean distribution in Chile, especially along the coastline between the Arica y Parinacota and Coquimbo regions. While both simplistic (with TNA = 8.0 °C) and presence-species methodologies showed similar behavior in the inland area, the main barrier for castor bean adaptation in that zone is the water regimen; however, castor bean could grow with irrigation.

Finally, both methodologies concluded that the most suitable land is between the Maule and Araucanía regions, although castor bean has not been registered in those regions. The simplistic methodology determined that 164,052 ha of suitable land with humid regime aptitude was registered between the Maule and Araucanía regions. With the presence-species methodology, 11,851 ha with mild thermic restriction and without hydric restriction was registered between the Biobío and Araucanía regions.

We conclude that both methodologies could be applied for castor bean determination, although the simplistic method, employed with TNA = 8.0 °C, showed high correspondence with its actual distribution in Chile.

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Appendix A

Table A1. Cities or towns in which castor bean has been registered; these were used to determine climate requirements for its development.

Country	City/Town	Geographic Coordinate		Reference
		Lat	Long	
Argentina	Buenos Aires	34°35′ S	058°29′ W	[40]
Argentina	Morón	34°39′ S	058°37′ W	[41]
Argentina	Paraná River	32°52′ S	060°40′ W	[41]
Argentina	Ensenada	34°50′ S	057°55′ W	[42]
Belize	Cayo	17°10′ N	089°01′ W	[42]
Bolivia	Andrés Ibáñez	17°47′ S	063°12′ W	[42]
Brazil	Cruz da Almas	12°40′ N	039°06′ W	[43]
Brazil	Garanhuns	08°53′ S	036°29′ W	[44]
Brazil	Presidente Bernandes	22°11′ S	051°40′ W	[45]
Brazil	Río Largo	09°27′ S	035°49′ W	[46]
China	Shangai	31°11′ N	121°32′ E	[47]
Costa Rica	San José	09°56′ N	084°04′ W	[42]
Costa Rica	La Garita de Alajuela	10°00′ N	084°16′ W	[48]
Cuba	Paraguay	20°03′ N	075°08′ W	[49]
Dominican Republic	Santo Domingo	18°31′ N	069°50′ W	[42]
Ecuador	Quito	00°08′ S	078°29′ W	[42]
Ecuador	Guayaquil	02°10′ S	079°50′ W	[42]
Gabon	Nyanga	03°41′ S	011°00′ E	[42]
Greece	Iraklion	35°18′ N	025°08′ E	[5]
Greece	Aliartos	38°22′ N	023°06′ E	[4]
Guyana Francesa	Cayenne	04°50′ N	052°17′ W	[42]
India	Delhi	28°40′ N	077°07′ E	[50]
India	Hyderabad	17°27′ N	078°28′ E	[51]
Iran	Esfahan	32°36′ N	051°26′ E	[52]
Israel	Tel Aviv	32°00′ N	034°49′ E	[53]
Italy	Bologna	44°33′ N	011°23′ E	[4]
Jamaica	Kingston	18°00′ N	076°47′ W	[42]
Madagascar	Antananarivo	18°54′ S	047°43′ E	[42]
Mexico	Tapachula	14°55′ N	092°14′ W	[42]
Mexico	Merida	20°58′ N	089°36′ W	[42]
Nicaragua	Jinotega	14°03′ N	085°29′ W	[42]
Paraguay	Central	25°50′ S	057°28′ W	[42]
Peru	Trujillo	08°07′ S	079°01′ W	[42]
Tanzania	Bukoba Rural	01°08′ S	031°27′ E	[42]
Tanzania	Kinondoni	06°48′ S	039°15′ E	[42]
Tanzania	Kilombero	02°34′ S	033°27′ E	[42]
Trinidad y Tobago	Port of Spain	10°25′ N	061°14′ W	[42]
Tunisia	Mateur	37°01′ N	009°52′ E	[17]
Tunisia	Mornag	36°41′ N	010°18′ E	[17]
Tunisia	Gabas	33°52′ N	010°07′ E	[17]
United States	Lubbock	33°36′ N	101°54′ W	[18]
United States	Tijuana River Valley	32°33′ N	117°04′ W	[54]
United States	Puerto Rico	18°28′ N	066°19′ W	[42]
United States	Alameda	37°52′ N	122°16′ W	[42]
United States	Jefferson	29°44′ N	090°06′ W	[42]
United States	Saint Louis	38°38′ N	090°27′ W	[42]
Uruguay	Montevideo	34°51′ S	056°10′ W	[42]

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