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Comments

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Article

Prediction of Cultivation Areas for the Commercial and an Early Flowering Wild Accession of *Salvia hispanica* L. in the United States

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Abstract: *Salvia hispanica* L., commonly known as chia, is a plant-based alternative to seafood and is rich in heart-healthy omega-3 fatty acid, protein, fiber, and antioxidants. In the Northern Hemisphere, chia flowering is triggered by the fall equinox (12-h light and dark, early October) and the seeds mature after approximately three months. Chia is sensitive to frost and end of season moisture which limits its cultivation to small areas in regions with temperate climate. The U.S. chia import has increased considerably over the years; however, chia is not widely cultivated in the United States. This study used the historical U.S. temperature and precipitation data as a first step to explore the potential of widescale chia cultivation. The 10th percentiles of 25 mm precipitation level as well as soft frost (32 °F: 0 °C) and hard frost (28 °F: −2.2 °C) were tabulated for the months of November and December. The results identified temperature as the main limiting factor for chia cultivation in the United States. The commercial chia variety (harvested in December) can be planted on approximately 10,000 km^2 cropland (1,000,000 hectare) in the United States. The future development of early flowering variety (harvested in November) was demonstrated to open an additional 44,000 km^2 (4,400,000 hectares) for chia cultivation in the United States. In conclusion, chia cultivation could provide economic benefits to U.S. farmers both by enriching the diversity within crop rotations aimed at reducing pest and pathogen populations and by its high economic value as an alternative specialty crop.

Keywords: frost; precipitation; agriculture; climate; vegan; omega-3 fatty acid; fiber; superfood; cardiovascular; antioxidant

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1. Introduction

Salvia hispanica L. (commonly known as chia) is an annual self-pollinated species within the mint family (Lamiaceae) and is native to central and southern Mexico and Guatemala [1]. Over the past 20 years, chia seed has been recognized as an important dietary food supplement since it provides remarkably balanced and close to complete nutrition. Chia seed contains 34% total dietary fiber, 31% total lipids, 16% protein, and 5.8% moisture. In addition, the seed contains high amounts (335–860 mg/100 g) of calcium, phosphorus, potassium, and magnesium, and its phytochemicals have antioxidant and antimicrobial properties [1–5]. The oil content of chia seed (31%) is higher than other commercial oilseeds, including soybean (24%) and cotton-seed (24%) [4]. More importantly, the fatty acids of chia seed oil are highly unsaturated, mainly containing alpha-linolenic fatty acid (ALA; also known as omega-3 fatty acid) (50–57%) and linoleic fatty acid (17–26%). This represents the highest known percentage of ALA of any plant source [1].

Chia is a re-emerged crop currently commercially produced in Mexico and Guatemala, South America (Bolivia, Colombia, Peru, and Argentina), Africa (Kenya, Tanzania, and

Uganda), and Australia [6,7]. In Mexico, the environmental conditions within the regions of Jalisco, Nayarit, Michoacán, Morelos, Puebla, México, Guerrero, Oaxaca, and Chiapas, are optimal for chia cultivation [8,9]. In 2013, 18,155 hectares were planted in Mexico with most of the production concentrated in the state of Jalisco (17,739 hectares). However, it was determined that Mexico holds a total of 2,512,359 hectares with an optimal or high cultivation potential under rainfed irrigation condition [8]. Species distribution models predicted chia could be grown as a rainfed crop in regions located near the Tropics of Cancer and Capricorn, in agreement with the tropical origins of the species [10]. The analysis identified the chia producing countries of Bolivia and Peru as well as several African countries such as Kenya, Angola, and Ethiopia as suitable areas. As expected, the model identified wider geographical regions where chia has the potential to be cultivated under irrigation. In Chile, 11,556 km^2 area in the Antofagasta region (northernmost part of the country) was identified as having a very suitable environment for chia cultivation under irrigation and an additional 163,224 km^2 area was deemed suitable and moderately suitable [10]. Being a re-emerged crop, chia has the potential to diversify the local agricultural economy as a profitable addition or even alternative to traditional crops. Chia is a particularly important oilseed crop in areas with limited water availability, as it is more drought tolerant than other oilseed crops [11]. Chia has been shown to adopt adaptive strategies under drought conditions that maintains its yield [12]. Due to its valuable nutritional qualities, the U.S. import of chia seeds increased over the last decade. In 2021, the United States imported USD 146.85 million worth of chia seeds from the rest of the world [11]. Most of the chia export to Europe is divided between Germany, Spain, the Netherlands, and the United Kingdom [13].

Chia is a short-day flowering plant species that is sensitive to frost [14]. In North America, chia seeds are planted in early spring after the last frost. During the following three months, plants grow lush vegetation and can become as tall as seven feet. Flowering is triggered during the autumnal equinox when the day and night have equal (12-h) lengths [15,16]. Thus, in the Northern Hemisphere, chia begins to flower in early October. Plants produce hundreds of long inflorescences that contain, on average, three seeds per calyx. By mid-December, the seeds mature and are ready for harvest. For optimal growth, chia requires irrigation or a well distributed rainfall during early growth and development and dry conditions during seed maturation and harvesting [17]. Rainfall after seed maturation results in extensive yield loss as moisture causes the seeds to release their polysaccharide mucilage, causing the seeds to adhere strongly and irreparably to the calyxes and to each other. Freezing temperatures after the autumnal equinox is another factor that limits chia cultivation as the emerged flower buds will be killed by frost before seeds set [1]

Low genetic diversity was documented among the domesticated chia accessions, which suggests a single origin of domestication. On the other hand, the total genetic diversity among the wild accessions studied was slightly greater compared to the domesticated accessions [18]. Similar conclusions were drawn from a recent genetic diversity analysis using 23,641 single nucleotide polymorphisms (SNPs) from eight different cultivated and wild accessions of *S. hispanica* L., where most of the variation was observed in wild populations [19]. Chia has not been the subject of many modern plant breeding efforts. Currently, there are few patented chia varieties that have long-day flowering characteristics. These varieties have been identified through selection and include variety Sahi Alba 912 and 913 from Peru, Sahi Alba 914 from Argentina [20], and Oruro from France [21]. An attempt was also made to develop an early flowering chia germplasm through mutagenesis induced by Ethyl methanesulfonate (EMS) and gamma radiation. Among the mutagenized plants, some were shown to flower at a daylength of 14 h and 41 min and have mature seeds by early October [16]. However, these long-day flowering chia lines were not utilized in commercial production possibly due to the lack of stability or uniformity of the long-day flowering phenotype. Through screening of wild-type chia germplasm collection, we identified a wild-type population that consistently flowers at a daylength of

13 h (early September) in California and produces mature seeds ready for harvest by early November [22]. Despite the presence of a number of domesticated varieties, the spotted (Pinta) variety is the most cultivated worldwide [18,23].

Given the high demand for chia in the United States as a healthy food supplement and its potential to diversify the local agricultural economy, the goals of this work are to (a) identify the suitable areas to cultivate the commercial chia variety "Pinta" in the United States and (b) determine the potential impact of a one-month earlier harvest date on chia cultivation. Overall, the results show that the potential cultivation of the commercial Pinta variety would be mainly concentrated in California, Arizona, and South Texas. Moreover, the one-month early flowering characteristic, once introduced into the commercial variety, will open up, fivefold, more area of cropland in continental United States to chia cultivation.

2. Materials and Methods

To evaluate the response of potential chia cultivation in the Unites States to a shift in harvest time, three factors were considered (two climate variables and one land use/land cover) (see Table 1). The data on freezing in a particular area is important to determine whether it is suitable for growing chia. In addition, the occurrence of precipitation during the harvest time is important as excessive amounts can damage the crop prior to harvest. Lastly, only the areas (cropland areas) suitable for agriculture were considered in the analysis.

Table 1. Sources of data used in the study.

Type of Data	Source	Resolution	Time Scale
Precipitation	CHIRPS	0.05°	2000–2020
Temperature	MRCC	0.05°	1990–2020
Land Use/Land Cover	USDA	30 m	1997–2021

2.1. Temperature

The date in which there is likely the first occurrence of freezing was identified using Date of First Freeze (28 °F and 32 °F, Note: 32 °F = 0 °C, 28 °F = −2.2 °C) from the Midwestern Regional Climate Center considered at the 10th percentile. The 10th percentile is a threshold where there is a 10% chance in any given year that a freeze could occur for the given date (November and December in this study) [24]. This data are available at a 0.05° resolution for the entire continental United States.

2.2. Precipitation

The occurrence of precipitation during the seed maturation months was calculated using the Climate Hazards center InfraRed Precipitation with Station data (CHIRPS) rainfall data, which is available at 0.05° resolution [25]. Daily precipitation data were considered from 1990–2020 for the months of November and December.

Analysis was conducted to find when each grid point in the data set exceeded thresholds of 10 mm and 25 mm precipitation at the 10th percentile threshold. The percentile rank method was used to determine these values for each grid cell and either December or November precipitation:

1. Daily precipitation (n = total rainfall days in either December or November for all years) was ranked (m = 1 being largest);
2. Percentiles for each day were computed as $p = \frac{m}{n+1}$;
3. Only grid cells less than the 10th percentile for 10 mm and 25 mm thresholds were retained.

2.3. Land Use/Land Cover

The identification of appropriate land areas to grow chia was conducted using the U.S. Department of Agricultural, National Agriculture Statistics Service Cropland Data [26] for continental United States. This data represented areas in the United States where crops are grown (not total farmland) and it is assumed to represent suitable areas where chia could be grown if appropriate environmental conditions are present (see next section). In total, there is approximately 2.1 million km^2 of cropland in the United States in regions with productive soils and large production of the global grain. These classes include various crops (corn, cotton, fruit, nuts, oils, rice, sugar, soybeans, vegetables and wheat). This is the second largest amount of cropland in the world with only India having more. Cropland in the United States is concentrated in the Corn Belt and Northern Plains regions, where several states (including Iowa, Kansas, and Illinois) have more than half of their land base devoted to cropland [27]. In California, most of the cropland is concentrated in the Central Valley (San Joaquin and Sacramento valleys) and the Central Coast (Figure 1).

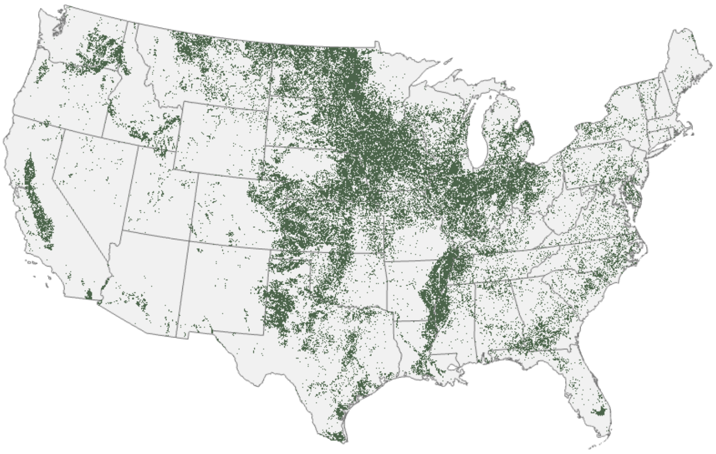

Figure 1. Land use representing cropland in the continental United States based on data from USDA Cropland Data.

2.4. Analysis of Climate and Land Use

A total of five scenarios are presented for this work to identify suitable areas to cultivate the commercial "Pinta" variety and to demonstrate the potential impact of a one month shift in chia harvesting from December to November. This includes:

1. Areas where temperatures are suitable based on either 28 °F (−2.2 °C) or 32 °F (0 °C);
2. Areas where precipitation is suitable based on thresholds of 10 mm and 25 mm;
3. Areas where land cover/land use is suitable based on cropland as the classifier (see Figure 1);
4. Areas that are suitable based on a combination of temperature and precipitation results from (1) and (2) combined;
5. Areas that are suitable based on a combination of temperature, precipitation, and land cover/land use results from (1), (2) and (3) combined.

All analyses were conducted using ArcGIS Spatial Analyst [28].

3. Results

The various analyses/scenarios are presented in Table 2 demonstrating where the commercial Pinta variety can be cultivated in the United States and the potential impact of shifting chia harvest time from December to November.

Table 2. Summary of all analyses presented in Figures 2–9. Results show the area in km^2 of the continental United States that meet the temperature, precipitation, or land use criteria (note: 32 °F = 0 °C, 28 °F = −2.2 °C).

	December (km^2)	November (km^2)	November/ December
Temperature Only			
28 °F (10th percentile)	393,048	2,074,239	5.3
32 °F (10th percentile)	148,407	1,161,492	7.8
Precipitation Only			
10 mm (10th percentile)	2,998,632	1,739,201	0.6
25 mm (10th percentile)	5,507,917	3,719,419	0.7
Temperature and Precipitation			
10 mm and 28 °F (10th percentile)	60,242	127,231	2.1
25 mm and 28 °F (10th percentile)	126,948	386,552	3.0
10 mm and 32 °F (10th percentile)	18,823	101,615	5.4
25 mm and 32 °F (10th percentile)	35,193	289,655	8.2
Temperature and Precipitation and Land Use			
25 mm and 28 °F (10th percentile)	29,484	62,224	2.1
25 mm and 32 °F (10th percentile)	10,379	54,393	5.2

3.1. Temperature

The first freeze temperature data in the U.S. for the months of November and December is presented in Figures 2 and 3. At the 10th percentile and considering 32 °F temperature (soft freeze), the amount of area is approximately eight times (8×) larger in November than December (1,161,492 km^2 vs. 148,407 km^2, Figure 2a). At the 10th percentile and considering a hard freeze of 28 °F, the amount of area is approximately five times (5×) larger in November than December (2,074,239 km^2 vs. 393,048 km^2, Figure 2b). The regions suitable for chia cultivation based on the given temperature thresholds are focused primarily in the southwest, west coast, south, and east coast.

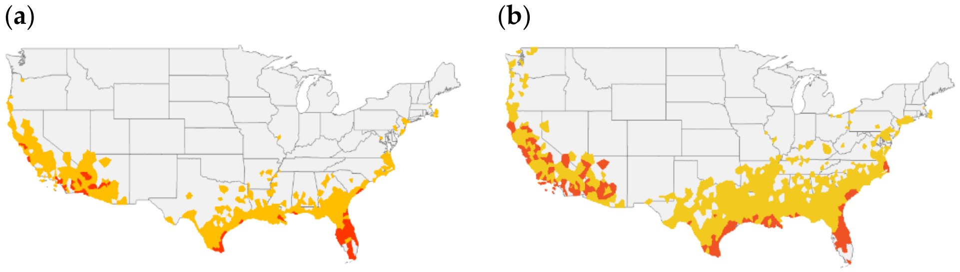

Figure 2. Thirty-year U.S. temperature below 10th percentile during months of November and December. (**a**) 32 °F 10th percentile and (**b**) 28 °F 10th percentile. Red color represents the areas that have less than a 10% chance of freeze during the month of December, and the combination of red and orange colors represents the data for the month of November (note: 32 °F = 0 °C, 28 °F = −2.2 °C).

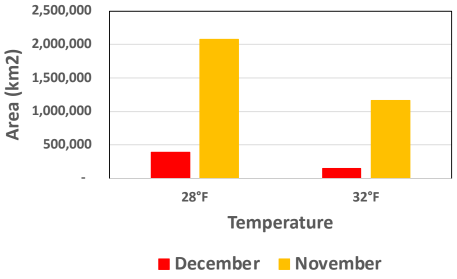

Figure 3. Quantification of the areas (km^2) in Figure 2 for 32 °F and 28 °F note: 32 °F = 0 °C, 28 °F = −2.2 °C).

3.2. Precipitation

The precipitation data below 10th percentile of 10 mm and 25 mm quantities in the United States is presented in Figures 4 and 5. At the 10th percentile and assuming a 10 mm precipitation threshold, the amount of area that does not receive this amount is 72% larger in December (approximately 3.0 million km^2) (Figure 4a) compared to November (approximately 1.7 million km^2) (Figure 4c). Similarly, using a precipitation threshold of 25 mm and 10th percentile, the amount of area that does not receive this amount is 48% larger in December (approximately 5.5 million km^2) (Figure 4b) compared to November (approximately 3.7 million km^2) (Figure 4d). Altogether, the results show that November is wetter in the Unted States compared to December and, if only precipitation is considered as a factor, there is not an advantage to shifting chia harvesting from December to November.

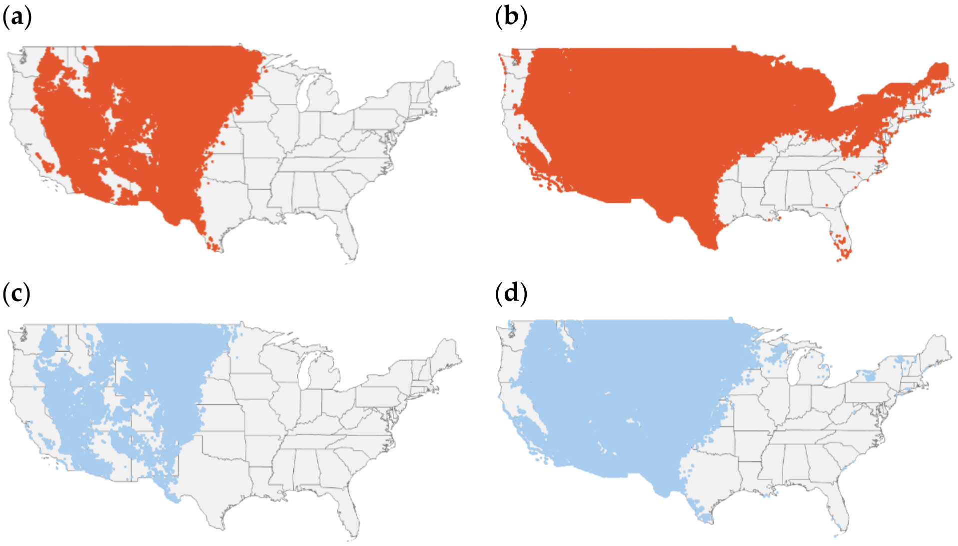

Figure 4. Thirty-year U.S. precipitation below 10th percentile during months of November and December. (**a**) 10 mm rainfall in December (**b**) 25 mm rainfall in December (**c**) 10 mm rainfall in November (**d**) 25 mm rainfall in November.

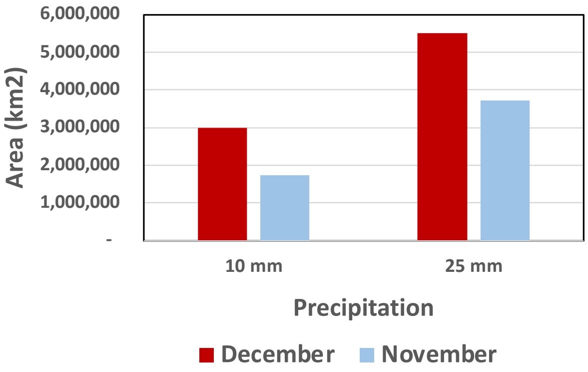

Figure 5. Comparison of areas in Figure 4a–d.

3.3. Precipitation and Temperature

The combination of the precipitation and temperature data, as two important environmental factors, will identify areas that provide suitable environmental conditions for potential chia cultivation in the United States. Figures 6 and 7 present the data with fixed precipitation quantity of 25 mm and two temperature scenarios (32 °F and 28 °F, 0 °C and −2.2 °C) for the months of November and December. Using a threshold of 25 mm, 10th percentile, and 32 °F, the identified area meeting this criterion is eight times (8×) larger in November (approximately 290,000 km^2) (Figure 6b) compared to December (approximately 35,000 km^2) (Figure 6a). At the 10th percentile, assuming a 25 mm precipitation threshold and 28 °F criteria, the identified area meeting this criterion is three times (3×) larger in November (approximately 387,000 km^2) (Figure 6d) compared to December (approximately 127,000 km^2) (Figure 6c). The quantification and the comparisons of these areas are shown in Figure 7.

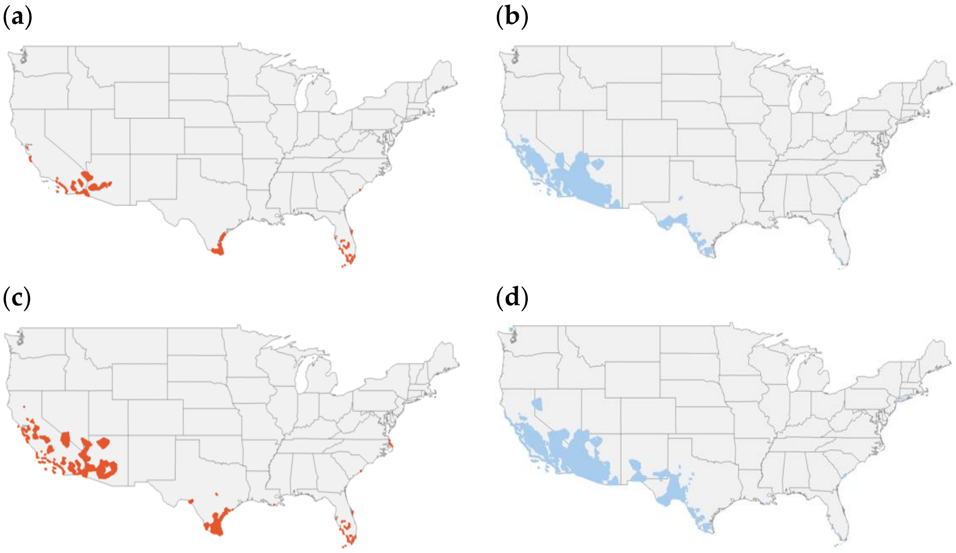

Figure 6. Combination of precipitation (25 mm threshold) and temperature (at 32 °F and 28 °F) for November and December (all 10th percentile) note: 32 °F = 0 °C, 28 °F = −2.2 °C). (**a**) 25 mm rainfall and 32 °F in December (**b**) 25 mm rainfall 32 °F in November (**c**) 25 mm rainfall and 28 °F in December (**d**) 25 mm rainfall and 28 °F in November.

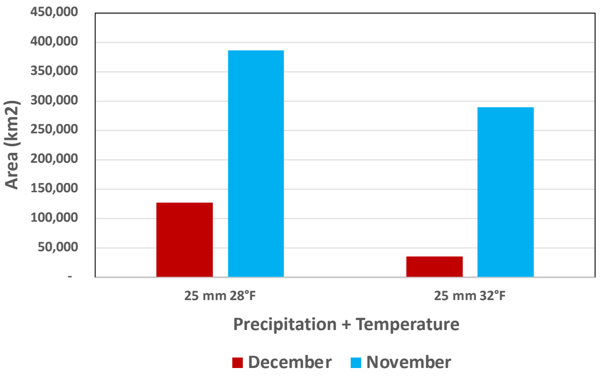

Figure 7. Comparison of all combinations of precipitation (25 mm threshold) and temperature (at 32 °F and 28 °F) for November and December (all 10th percentile) (note: 32 °F = 0 °C, 28 °F = −2.2 °C).

Similar trends were observed when the lower precipitation quantity of 10 mm (more stringent scenario) was combined with the 32 °F and 28 °F (0 °C and −2.2 °C) temperature thresholds. With the 32 °F temperature threshold, the amount of area is five times (5×) larger in November than December (102,000 km^2 vs. 19,000 km^2). With the 28 °F temperature threshold, the amount of area is two times (2×) larger in November than December (127,000 km^2 vs. 60,000 km^2).

3.4. Precipitation, Temperature and Land Use/Land Cover

The final analysis mapped the areas in the United States with environmental conditions (precipitation and temperature) suitable for chia cultivation to currently available cropland areas (Figures 8 and 9). Similar to the analysis in Section 3.3, only the 25 mm precipitation threshold combined with both the 28 °F and 32 °F (−2.2 °C and 0 °C) is shown. Using a threshold of 25 mm, 10th percentile, 32 °F, combined with cropland areas, the area meeting this criterion is approximately five times (5×) larger in November (54,000 km^2) (Figure 8b) compared to December (approximately 10,000 km^2) (Figure 8a). On the other hand, at the 10th percentile, assuming a threshold of 25 mm precipitation and 28 °F, combined with cropland areas, the identified area meeting these criteria was approximately two times (2×) larger in November (62,000 km^2) (Figure 8d) compared to December (29,000 km^2) (Figure 8c). The quantification and the comparisons of these areas are shown in Figure 9.

Figure 8. Combination of precipitation (25 mm threshold) and temperature (32 °F and 28 °F) for November and December within cropland areas (note: 32 °F = 0 °C, 28 °F = −2.2 °C). (**a**) 25 mm rainfall and 32 °F in December (**b**) 25 mm rainfall 32 °F in November (**c**) 25 mm rainfall and 28 °F in December (**d**) 25 mm rainfall and 28 °F in November.

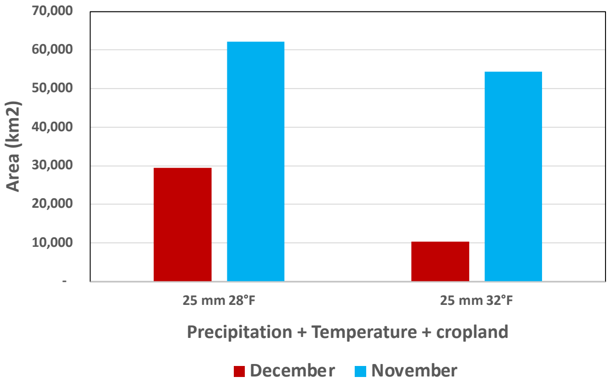

Figure 9. Comparison of all combinations in Figure 8a–d (note: 32 °F = 0 °C, 28 °F = −2.2 °C).

To obtain more specific information regarding the regions in southwest United States suitable for chia cultivation based on land use/land cover, precipitation, and temperature, the results shown in Figure 9 are presented at county levels for each of the states of California, Arizona, and Nevada (Figure 10). These represent active farming areas that do not have the extreme cold temperatures in the winter that would limit chia growing.

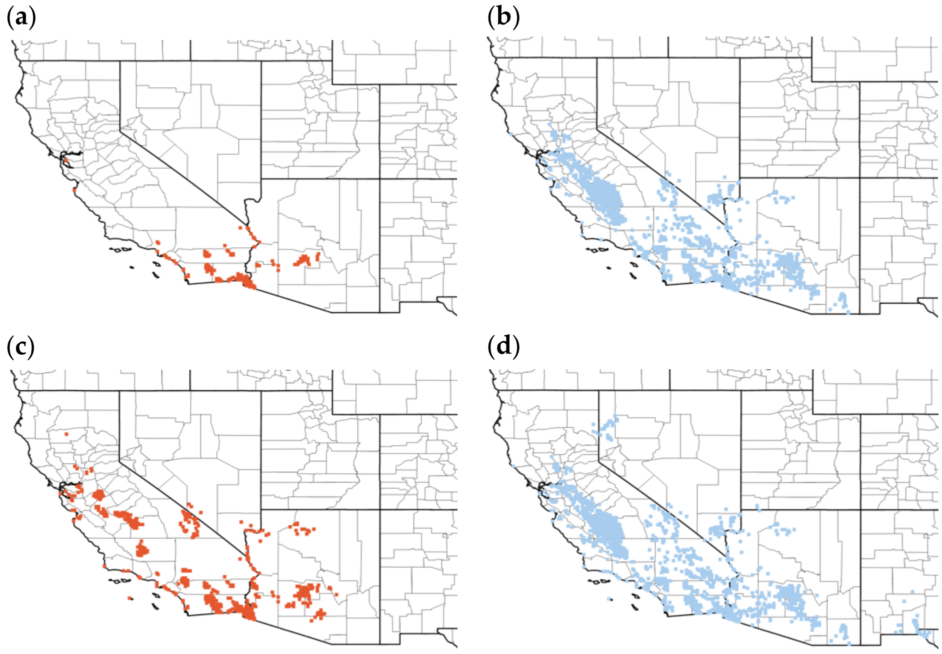

Figure 10. Areas in southwest United States (by counties) where Chia could be potentially grown based on land use, precipitation, and temperature criteria (note: 32 °F = 0 °C, 28 °F = −2.2 °C). (**a**) 25 mm rainfall and 32 °F in December (**b**) 25 mm rainfall 32 °F in November (**c**) 25 mm rainfall and 28 °F in December (**d**) 25 mm rainfall and 28 °F in November.

4. Discussion

Due to the recent public interest in healthier lifestyles, the demand for functional foods with multiple health benefits has increased in the United States and worldwide [1]. Chia is one such functional food that provides balanced nutrition and oil content with high unsaturated fatty acids documented to decrease the risk of cardiovascular diseases (CVDs) [29,30]. Despite the high demand for chia seed, the U.S. produces small amounts of chia. This is mainly due to lack of research on this crop, since for over 600 years chia was only cultivated locally in Mexico. Research is needed to acquire better understanding of the interactions of the chia crop with the U.S. environment, its production capabilities in terms of yield, and the economic benefits that it can bring to the farmers.

In general, many factors influence the decision of farmers to adopt a new crop. In the United States, agricultural industrialization resulted in a shift from small family-owned farms to agribusinesses and large farming operations [31]. These farms specialize in few crops and utilize specialized equipment to reduce labor costs and increase production efficiency. Therefore, the U.S. farmers may find it difficult to adopt new crops due to high initial costs to purchase specialized equipment [32]. The farmers' decision also depends on the crop characteristics, especially those related to the agronomic performance such as yield as well as marketability. Thus, insufficient knowledge and technical skills and lack of marketing information, which altogether increase the risk factor, often discourage farmers [32].

The first step towards future incorporation of chia in the U.S. agricultural system is the need to identify locations in continental United States with suitable environments for its cultivation. Frost and end of season precipitation are the two main factors that limit chia production. By creating species distribution model based on precipitation and temperature variables, Cortes et al. (2017) identified regions suitable for chia cultivation in Chile under irrigation. According to their result, around 23% of Chile was identified as having a very suitable to moderately suitable environment for chia cultivation. Here we present the potential chia cultivation areas in the United States for the most cultivated variety in the world (Pinta; harvested in December) and the potential impact of a one-month earlier harvest date (November) on chia cultivation in the United States. Based on the historic 30-year temperature data, most of the continental United States sees its first soft frost (32 °F) during the month of December with more than 10% probability. Exceptions include some parts of California, Arizona, South Texas, and Florida. Cold stress is a major problem in agriculture as it has adverse effects on the growth and survival of a large number of crop species, limiting their geographical distribution [33]. While the development of frost tolerant chia varieties will result in significant increase in cultivation area, it will be very challenging as chia is an annual warm season crop and natural genetic sources probably do not exist. The month of November is relatively warmer, and adds significant portions of California, Arizona, and the south of the country between Texas and Florida as potential regions for chia cultivation. In terms of precipitation, the United States is generally wetter during the month of November compared to December at both 10 mm and 25 mm thresholds, but the differences are not considerable. Thus, based on our results, humidity at the end of the season is not a major constraint for chia cultivation in the United States. Collectively, these data show that developing earlier flowering chia varieties, that can be harvested before the first frost, should be the priority in future breeding programs as it has the potential to significantly increase the areas where chia can be cultivated in the United States.

The suitability of environmental conditions in a given geographic location should not encourage the degradation of the natural ecosystems by converting them to agricultural lands. Mapping the current U.S. cropland areas to these locations identified California, Arizona, and South Texas as the main states where chia can be successfully cultivated. The development of new varieties that can be harvested a month earlier in November is expected to open an additional 54,000 km^2 area (5.4 million hectare), an approximately five times (5×) larger area compared to where the commercial Pinta variety can be planted in the United States. Our results are in agreement with a world species distribution model that identified the southwest United States as suitable region for chia cultivation under irrigation [10]. Around 0.1–0.3% of the United States is suitable for chia cultivation compared to 23% reported in Chile. However, direct comparison cannot be made since the results reported for Chile represent the total area, and the percentage of suitable areas would drop significantly below 23% after adding cropland as an additional variable. Given the worldwide increase in the demand of chia seeds in the future, it is possible that chia cultivation in the United States will be profitable to the farmers. Multi-location field trials are needed in California and Arizona to document the average yield per acre and accordingly conduct economic studies looking into the profitability of chia cultivation.

5. Conclusions and Future Perspectives

In this study, we show the overall prospects of chia cultivation in the United States at county level based on two key environmental factors and demonstrate the importance of developing early flowering varieties that can be harvested before the first freeze. Being a re-emerged crop, research on chia is still at its infancy. More research is needed to gain a better understanding of the crop and its interaction with the U.S. environmental conditions beyond temperature and precipitation. With the demand for chia seeds expected to increase over time, chia cultivation in the U.S. could be profitable for the farmers. It would provide them with an extra crop that they can integrate into their crop rotations over the years to reduce pest and pathogen populations without compromising profits. Thus, more studies are needed to address the economic, environmental, social, and institutional factors associated with chia cultivation in the United States.

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Conflicts of Interest: The authors declare no conflict of interest.

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