The American Journal of Clinical Nutrition 119 (2024) 58–68

American Society for Nutrition
Excellence in Nutrition Research and Practice

The American Journal of
CLINICAL NUTRITION

journal homepage: https://ajcn.nutrition.org/

Original Research Article

Climate-based variability in the essential fatty acid composition of soybean oil

Michael R. Bukowski [1,*], Sarah Goslee [2]

[1] Methods and Application of Food Composition Laboratory, Beltsville Human Nutrition Research Center, USDA-ARS, Beltsville, MD, United States;
[2] Pasture Systems & Watershed Management Research Unit, USDA-ARS, University Park, PA, United States

ABSTRACT

Background: Soybean oil is a major dietary source of the essential fatty acids linoleic acid (LA) and α-linolenic acid (ALA); however, high-daytime temperatures during seed development reduce desaturase activity in soybeans. The resultant reduction in LA and ALA levels is a phenomenon well-known to soybean breeders, although the impact of this interaction between plants and environment on human nutrition is poorly understood.

Objectives: Using data from the literature, we developed a model for soybean essential fatty acid composition. Combining this model with contemporary agricultural and meteorological data sets, we determined whether insufficiency of essential fatty acids could result from geographic, intrayear, or interyear variability.

Methods: We modeled this change using 233 data points from 16 studies that provided fatty acid composition data from plants grown under daytime high temperatures ranging from 15°C to 40°C.

Results: As temperature increased, LA and ALA concentrations decreased from 55% to 30% and 13% to 3.5%, respectively. Application of the model to daytime high temperatures from 2 growth periods over 6 y showed significant regional, interyear, and intrayear variation in essential fatty acid content ($P < 0.05$). Using county yield data, we developed oil fatty acid models for the 3 top-producing regions of the United States. From this work, it was determined that soybean oil manufactured from soybeans in the southern United States may contain insufficient ALA to meet human nutritional needs because of high-daytime temperatures.

Conclusions: This work suggests that climate-based variation may result in many human populations not achieving an adequate daily intake of ALA.

Keywords: soybean oil, temperature effects, α-linolenic acid, linoleic acid, climate change, human nutrition

Introduction

Predicting the impact of climate change on human nutrition is challenging because most crop models use yield as the primary end point. In recent decades, models developed for nutritional staples, including maize [1,2], potatoes [3,4], wheat [5], and other crops [6–8], have been used to predict the impact of precipitation, irrigation, nitrogen, organic matter, and other agronomic factors on yield. Some factors in climate change can increase yield while decreasing the nutritional value of food. For example, increased atmospheric carbon dioxide concentration can increase yield in rice [9,10], wheat [11], potatoes [4], cassava [12], and beans [13] because of carbon dioxide-promoted carbohydrate synthesis, despite a decrease in nutritional metrics, such as protein and/or trace mineral content. One proposed mechanism suggests that elevated carbon dioxide concentration increases carbohydrate synthesis and storage, resulting in the dilution of other nutrients; however, changes in cultivar and transpiration may also play a role in this effect [13,14]. This is an example of how an extrinsic quality, such as yield, can mask intrinsic changes in nutritional quality that may result in “hidden hunger” [15]. In this work, we expand on this “hidden hunger" concept to include essential fatty acids.

Soybean oil is second only behind palm oil as the most commercially abundant plant oil globally [16]. During 2016–2021, the global consumption of soybean oil averaged 56.3 million metric tons annually (Figure 1). Excluding oil diverted for industrial and biofuel use [17], 45.4 million metric tons of soybean oil entered the food supply, representing 29.0% of all plant-based food oils consumed. This is

---

Abbreviations: EMG, early-maturing group; FAD, fatty acid desaturase; FDC, FoodData Central; LA, linoleic acid; ALA, α-linolenic acid; MMG, midmaturing group; NASS, National Agricultural Statistics Service; OA, oleic acid; ERS, Economic Research Service.

* Corresponding author.

E-mail address: michael.bukowski@usda.gov (M.R. Bukowski).

https://doi.org/10.1016/j.ajcnut.2023.08.024
Received 15 May 2023; Received in revised form 22 August 2023; Accepted 31 August 2023; Available online 30 November 2023
0002-9165/Published by Elsevier Inc. on behalf of American Society for Nutrition.

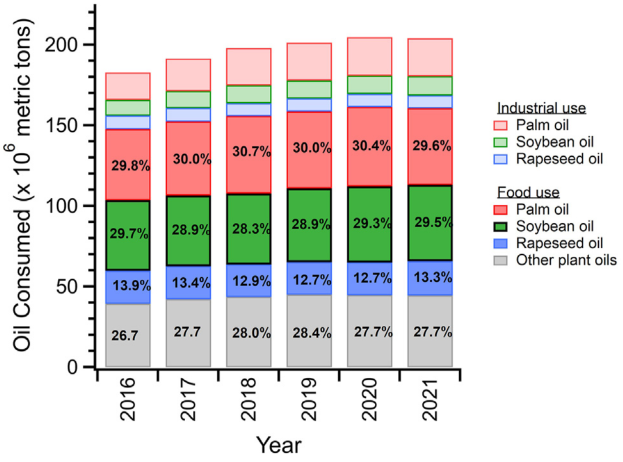


Figure 1. Global oil consumption from USDA Economic Research Service, Oil Crops Yearbook [16] and USDA FAS Production, Supply, and Distribution database [17]. For each year, columns are ordered by descending contribution, with palm, soybean, and rapeseed oils, respectively. The category "all other plant oils" includes, in descending order of contribution, sunflower seed, palm kernel, peanut, cotton seed, coconut, and olive oils. Percentages represent the percent of food-grade oil consumed that year. Industrial oils are shown for scale but not included in the calculation. FAS, Foreign Agricultural Service.

approximately twice the amount of the second-most consumed oil, rapeseed (including canola, 13.2%), and over 15-times more than olive oil (1.9%). Soybean oil is a staple dietary fat in human nutrition [18].

Nutritionally, soybean oil is high in unsaturated fats, such as oleic acid (OA), linoleic acid (LA), and α-linolenic acid (ALA, Table 1), and represents an important way for consumers to reduce the intake of SFAs, as recommended in the Dietary Guidelines for Americans [19]. LA and ALA are essential fatty acids that must be obtained through dietary intake. In the American diet, soybean oil is the most common source of LA and ALA [20]. Additionally, diets high in LA and ALA, essential omega-6 and ω-3 fatty acids, respectively, have been linked with a decreased risk of cardiovascular disease and reductions in concentrations of cardiovascular disease risk markers, such as total cholesterol, LDL cholesterol, and plasma triacylglycerol [21–24].

Fatty acid composition of soybean varies with both cultivar and environment [25]. Soybeans are uniquely suited for this study because there is a well-characterized biochemical mechanism underlying the relationship between temperature and fatty acid composition. The global ubiquity of soybean as a commodity crop makes modeling climate effects relevant across diverse environments. Mechanistically, the major factors impacting the LA and ALA content in soybeans are the activity of fatty acid desaturase (FAD) enzymes, FAD2 and FAD3, respectively [26,27]. As temperature during seed development increases, FAD3 activity decreases in soybeans, wheat, and peanuts [28–32]. As first reported over 65 y ago [33], the critical determinant for fatty acid composition is daytime high temperature during the pod-filling stage of seed development [32], denoted reproductive stage 5 (R5) [31,34]. Genetic factors impacting the rate of plant development, including sensitivity to photoperiod and temperature, result in cultivars of different maturity groups (early-, mid-, or late-maturing) reaching the seed-filling stage of soybean development (reproductive stage 5 [R5]) at different points in the growing season [35]. Development during R5 is responsible for ~79% of seed-storage lipids in soybeans [36], and increases in temperatures during this period reduce the activity and expression of FAD enzymes [31,32,37]. Soybean is planted across a wide range of latitudes per the maturity group, which should result in geographic variability in fatty acid composition [38]. Additional intrayear variability may result from double cropping, where soybean is planted after another crop in the same year [39]. The broad cultivation of soybean and its vital agricultural, economic, and nutritional roles have led to extensive crop modeling to assess the impact of climate change on yield [1,8,40–45], although the connection with compositional outcomes regarding nutrition remains unclear.

Table 1
Average fatty acid composition and human health relevance for soybean oil components

Composition[1]	Fatty acid	Type	Relevance
22.1%	OA	MUFA	nonessential
50.9%	LA	PUFA; ω-6	essential in diet
6.62%	ALA	PUFA; ω-3	essential in diet
14.9%	SFA		linked to negative health outcomes

Abbreviations: ALA, α-linolenic acid; LA, linoleic acid; OA, oleic acid.

[1] United States Department of Agriculture, Agricultural Research Service. Food Data Central 2022 [cited February 1, 2023]. Available from: https://fdc.nal.usda.gov/.

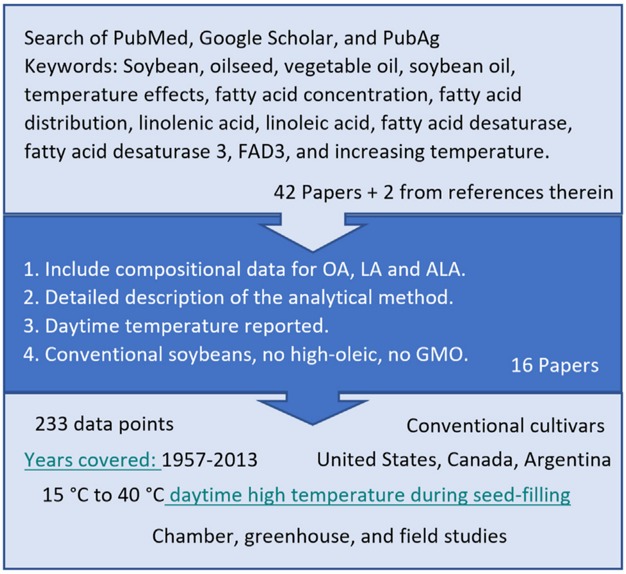
A decrease in the concentration of essential fatty acids has a profound nutritional impact, and accurate composition data for soybean oil are essential for determining its dietary status. High-OA–producing soybean cultivars bred for improved shelf stability have lower ALA and LA levels, and replacement of conventional soybean oil with high-OA blends can put some populations at risk of insufficient daily ALA intake [46], with such blends resulting in ALA concentrations of $\leq$5.68%. Subsequent dietary modeling work for children aged 1–8 y suggested inadequate ALA intake for children at concentrations equivalent to 5% ALA [47]. Here, we demonstrate that ALA concentration can decline to this level in conventional soybean oil because of increasing temperatures during the growing season. We construct a general model for fatty composition as a function of daytime high temperature from publicly available data, illustrate significant geographic, interyear, and intrayear variation in essential fatty acid content, and determine the fatty acid concentration for model oils from 3 regions of the United States.

Methods

Literature search and data selection

Literature values for soybean fatty acid composition were gathered according to the applicable methods detailed in the PRISMA Extension for Scoping Reviews [48], as shown in Figure 2. Using the search engines PubMed, Google Scholar, and PubAg, queries were generated with the following search terms in different combinations and orders: soybean, oilseed, vegetable oil, soybean oil, temperature effects, fatty acid concentration, fatty acid distribution, linolenic acid, linoleic acid, fatty acid desaturase, fatty acid desaturase 3, FAD3, and increasing temperature. The search included all results up to July 2022. Full-text articles were evaluated per the following criteria:

1) Included studies should be original research articles containing primary data. Review data were excluded from the study.
2) Articles must include fatty acid compositional data for OA, LA, and ALA, with a detailed description of the analytic method by which they were obtained from the soybean seed. Articles without experimental details that described how fatty acid profiles were obtained were excluded.



Search of PubMed, Google Scholar, and PubAg
Keywords: Soybean, oilseed, vegetable oil, soybean oil, temperature effects, fatty acid concentration, fatty acid distribution, linolenic acid, linoleic acid, fatty acid desaturase, fatty acid desaturase 3, FAD3, and increasing temperature.

42 Papers + 2 from references therein

1. Include compositional data for OA, LA and ALA.
2. Detailed description of the analytical method.
3. Daytime temperature reported.
4. Conventional soybeans, no high-oleic, no GMO.

16 Papers

233 data points
Conventional cultivars
Years covered: 1957-2013
United States, Canada, Argentina
15 °C to 40 °C daytime high temperature during seed-filling
Chamber, greenhouse, and field studies

Figure 2. Flowchart for the selection of literature sources and data for modeling.

3) Temperature data during seed filling must be reported. For field studies, reports of daytime high temperatures during seed development were deemed appropriate. For controlled-environment studies, reports of high temperatures during the daylight phase of growth were required. Night-time temperatures were not assessed. Studies reporting seasonal averages were excluded from the model.
4) Conventional soybeans were included in the analysis, but high-OA varieties were not considered. Soybean cultivar information was desirable but not required for inclusion.

All literature obtained from this search were evaluated manually from the corresponding author, and citations were reviewed to evaluate additional data sources. Two additional studies were added in this manner. Data are presented in Supplementary Table S1.

Model development

Data for OA, LA, and ALA were fitted by regression to a sigmoidal function (Equation *1*). Because SFA reporting was not consistent over the period examined, all SFAs were expressed as a group sum. The total SFA values were modeled by linear regression. All regressions included both confidence and prediction bands (Figure 3). Model-fit parameters for sigmoidal functions for LA and ALA are reported in Table 2.

$$m_{FA} = c_1 + \left(\frac{c_2}{\left(1 + e^{\frac{\mu - T}{c_3}}\right)} \right) \qquad 1$$

where m_{FA} is the mass percent of a fatty acid; T is the daytime high temperature (°C); and c_1, c_2, c_3, and μ are fitting coefficients in Igor Pro 8 (Wavemetrics, Inc.).

Determining distribution of soybean crop and dates of seed filling

Two data sets were used to model soybean development to determine local daytime high temperatures during seed filling. Production data were obtained at the county-level from the National Agricultural Statistics Service (NASS) Quick Stats Database [49] and converted from bushels to kilograms of soybean oil using conversion factors from the United States Soybean Export Council [50]. Planting progress for

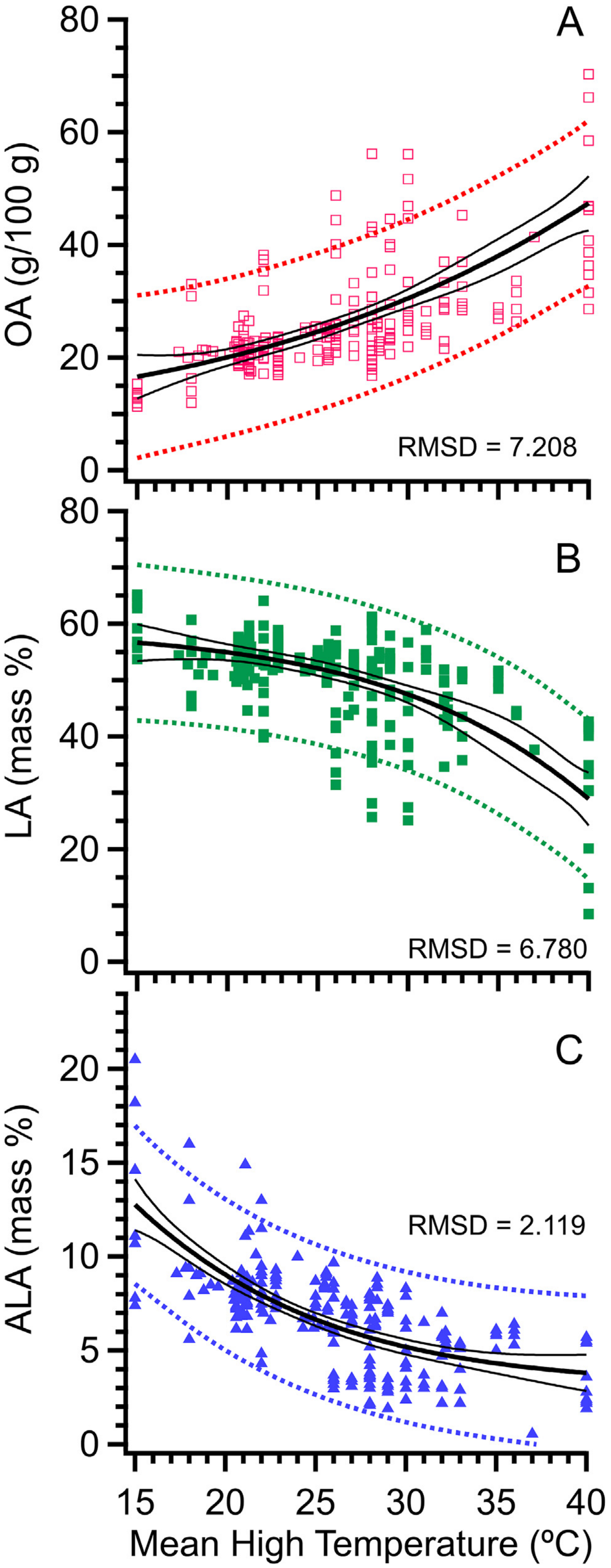


Figure 3. Models of soybean fatty acid response to temperature from references in Supplementary Table S1 for (A) OA, (B) LA, and (C) ALA. The thick black line represents the best fit; thin black lines represent 95% confidence intervals; dashed lines represent 95% prediction interval with RMSD reported for each model. Fit coefficients are presented in Table 2. ALA, α-linolenic acid; LA, linoleic acid; OA, oleic acid; RMSA, root mean square deviation.

Table 2

Model coefficients for fatty acid composition models in Equation *1*

Coefficient	Fatty acids[1]		
	OA	LA	ALA
c_1	7.0586	59.231	64.957
c_2	179.53	−220.58	−65.036
c_3	15.225	9.6018	16.241
μ	58.853	57.627	−10.969

Abbreviations: ALA, α-linolenic acid; EMG, early-maturing group; LA, linoleic acid; MMG, midmaturing group; OA, oleic acid.

[1] SFA were modeled by linear regression (slope = 0.14764, intercept = 12.829, and r^2= 0.0509).

2016–2021 were obtained from the criteria shown in Supplementary Table S2. Planting dates for the years 2016–2021 were assessed using reported weekly sowing progress statistics for each state with the parameters in Supplementary Table S2. The planting data were reported by NASS as cumulative weekly progress recorded for the week of the year (e.g., week 1–52). To determine the typical date for planting, the first derivative of weekly planting progress data was taken. Derivatives were aligned by week and normalized for each state over the 6-y range (Supplementary Figure S2). The first maximum for each state was used to establish a representative planting week for the counties there, which was correlated to the day and month for each year from 2016 to 2021.

Using the development model of Fehr and Caviness [34], we considered 2 classes of soybean, early-maturing (EMG) and mid-maturing groups (MMG), with pod-filling occurring between 39 and 50 d postplanting and 74–89 d postplanting, respectively. The addition of these durations to the planting dates defined the date ranges for meteorological data (Supplementary Table S3).

Meteorological data

The USDA NASS Cropland Data Layer 30-m data set was intersected with a 4-km gridMET climate grid to identify climate grid cells containing $\geq$5% cover of soybeans in any year from 2008 to 2021 [51, 52]. This approach excluded possible interference because of elevated temperatures from land used for nonagricultural purposes and excluded nonrepresentative temperatures in portions of counties not suitable for soybean production. Daily minimum and maximum temperatures for soybean-producing areas were averaged across each county. Finally, the means (SDs) for daily maximum temperatures were calculated across the key soybean physiologic date ranges described above (Supplementary Table S3). Spatial climate analyses were conducted using the raster package in the statistical program R [53,54].

Generation and analysis of fatty acid data

The mean daytime high temperatures for each county for EMG and MMG soybeans were input into the model (Equation *1*) with the corresponding coefficients for OA, LA, and ALA as shown in Figure 4 (Supplementary Figures S3, S4). Counties were grouped by the latitude of the county polygon centroid in 5° increments with A, B, C, D, and E covering ranges from 25°N–30°N, 30°N–35°N, 35°N–40°N, 40°N–45°N, and 45°N–49°N, respectively (Table 3, Figure 5). Counties contributing <0.015% to national soybean production were excluded from the interyear variability analysis.

Modeling soybean oil

Mapping the yield for the top 20% of soybean-producing counties showed 3 geographically distinct regions of high production (Supplementary Figure S5). The North was a 3-state region in or around the Red River Valley of MN, ND, and SD. The Central region contained

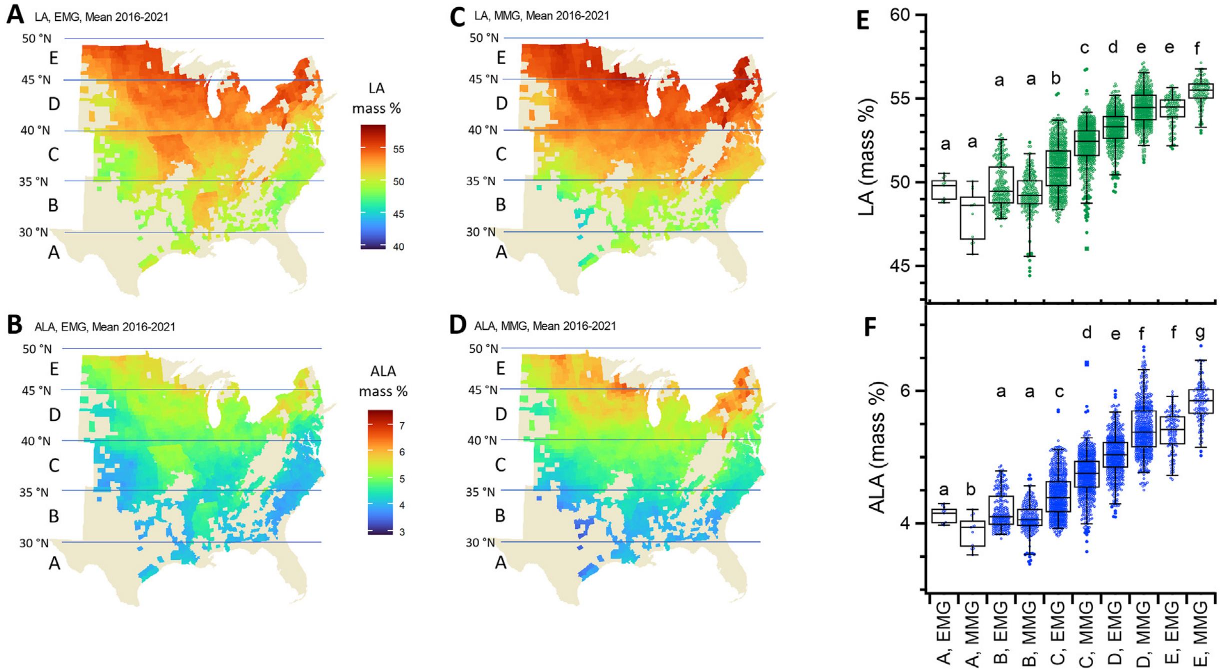


Figure 4. Geographic and intrayear variability in FA composition based on 5-y mean (2016–2021). Geographic variation in fatty acid concentration for EMG soybeans (A) LA and (B) ALA; MMG soybeans (C) LA and (D) ALA; and isolated by latitude in 5° intervals for (E) LA and (F) ALA. Box plots show the mean with second and third quartiles; whiskers extend to 2nd and 98th percentiles. Different letters represent differences by Bonferroni correction post hoc test at $P < 0.001$. Latitude delineations are not to scale. ALA, α-linolenic acid; EMG, early-maturing group; LA, linoleic acid; MMG, midmaturing group; OA, oleic acid.

TABLE 3

Predicted variation in fatty acid composition from 2016–2021 expressed as 6-y mean by latitude group and maturity group

Group	Latitude range	*n*	Maturity	LA[1] (% ± SD)	ALA (% ± SD)
A	25°N–30°N	11	EMG	49.6 ± 0.68	4.14 ± 0.13
			MMG	48.1 ± 1.52	3.88 ± 0.24
B	30°N–35°N	253	EMG	49.8 ± 1.34	4.19 ± 0.27
			MMG	49.3 ± 1.27	4.08 ± 0.22
C	35°N–40°N	699	EMG	50.9 ± 1.45	4.43 ± 0.32
			MMG	52.2 ± 1.30	4.73 ± 0.32
D	40°N–45°N	602	EMG	53.2 ± 1.06	5.03 ± 0.31
			MMG	54.4 ± 1.02	5.42 ± 0.37
E	45°N–49°N	126	EMG	54.3 ± 0.87	5.38 ± 0.30
			MMG	55.4 ± 0.78	5.83 ± 0.31

Abbreviations: ALA, α-linolenic acid; EMG, early-maturing group; LA, linoleic acid; MMG, midmaturing group; OA, oleic acid.

[1] Fatty acid concentrations are stated as mass percentage fatty acid with SD.

counties in IN and IL, while the South region stretched along the Mississippi River Valley between AR and MS. Soybean processing was regionally distributed across the United States [55]; within each region identified, 10 contiguous high-producing counties were grouped, and the soybean yield for each county was expressed as a fraction of the yield within that group (Supplementary Table S4). The fractional yield for each county was multiplied by the fatty acid distribution for each year, and the sum for each region by year is shown in Figure 6 along with fatty acid composition values from the USDA FoodData Central (FDC) Foundation Foods data set.

Statistical analysis and graphic representation

Statistical analyses were performed in RStudio 2022.12.0 Build 353 (Posit Software) running R version 4.2.1 [54] with the tidyverse library [56] and associated packages (ggplot2, usmap, and dplyer). Fatty acid composition values were compared across counties, maturity groups, and years using 3-way analysis of variance. Additionally, fatty acid values were grouped by latitude, year, and maturity group. These groups were compared by multiple paired *t* tests using the Bonferroni correction to control for type-1 errors. Box plots were constructed using Igor Pro 8 (Wavemetrics, Inc.).

Results

Assessment of literature

The literature review found 42 candidate articles, with 2 additional articles from citations there (Figure 2). After applying the screening criteria, data from 16 studies were included for analysis, resulting in a data set containing 233 data points for mean daytime high temperatures and fatty acid composition (Supplementary Table S1). Literature spanned the years 1957–2013 and represented a mix of growth-chamber, greenhouse, and field experiments [31,33,57–70]. Temperatures ranged from 15°C to 40°C. In some cases, temperature represented 1 of several variables, including land management [65] or drought stress [60]; however, the temperature-responsive fatty acid changes appeared to be independent of those variables.

The soybean cultivars represented various nontransgenic lines grown in the temperate regions of the United States, Canada, and Argentina. Because soybean oil in the human diet is a composite material representing various cultivars, individual cultivar contributions were not considered further.

Analytic techniques for determining the fatty acid composition reflected advances in methodology over time. Howell and Collins [33] employed a spectrophotometric method for the determination of LA and ALA, but OA and SFA were not measured. Two groups used near-infrared methods for fatty acid analysis, reporting SFAs (palmitic acid and stearic acid), OA, LA, and ALA [64,66]. The remaining studies employed fatty acid methyl ester analysis using gas chromatography after either acid-catalyzed [31,59] or base-catalyzed [57,58,60–63,65,67–69] transesterification. Data expressed as mass percentage are presented in Supplementary Table S1.

Modeling the fatty acid response

Fatty acid composition data extracted from the literature were plotted against the corresponding temperature data and fitted by regression to a sigmoidal function for OA, LA, and ALA. The model for SFA is shown in Supplementary Figure S1. Increasing temperatures from 15°C to 40°C decreased the concentrations of LA (55%–30%) and ALA (13%–3.5%). Fit parameters for the sigmoidal regression are presented in Table 2. Prediction and confidence intervals are displayed in Figure 3. For any conventional soybean sample, the fatty acid composition should fall within the predicted intervals (dashed lines) 95% of the time. In contrast, the confidence interval (solid line) shows the range where the mean for a population of soybeans grown at that temperature would occur, which is more representative of the composite nature of soybean oil reaching the consumer.

Determining daytime high temperatures from the planting date

Planting progress data for states followed 1 of 3 patterns. Some states had singular maxima between the 19th and 21st weeks of the year (Supplementary Figure S2, red bars). A pattern suggestive of double cropping appeared as 2 distinct planting date maxima, 1 around the 17th wk, and a second 3–5 wk later (Supplementary Figure S2, green bars) (39); however, NASS data on this practice were insufficient for inclusion in the model. For many states, planting occurred over ~6-wk, starting on or about the 18th week of the year (Supplementary Figure S2, blue bars). Variations in weather, planting practices, or state geography may all impact planting progress, although the absence of metadata, such as county or agricultural district planting progress, precluded attribution for the observed variation. For this model, the critical aspect was the observation that planting dates, and therefore maturity dates, are distributed throughout the growing season and thus lead to intrayear variability. This work used a single planting maximum and soybeans of differing maturity groups, early-maturing soybeans (EMG) and midmaturing soybeans (MMG), to examine this effect [34], although the observation of planting variability bolsters the argument for intrayear compositional

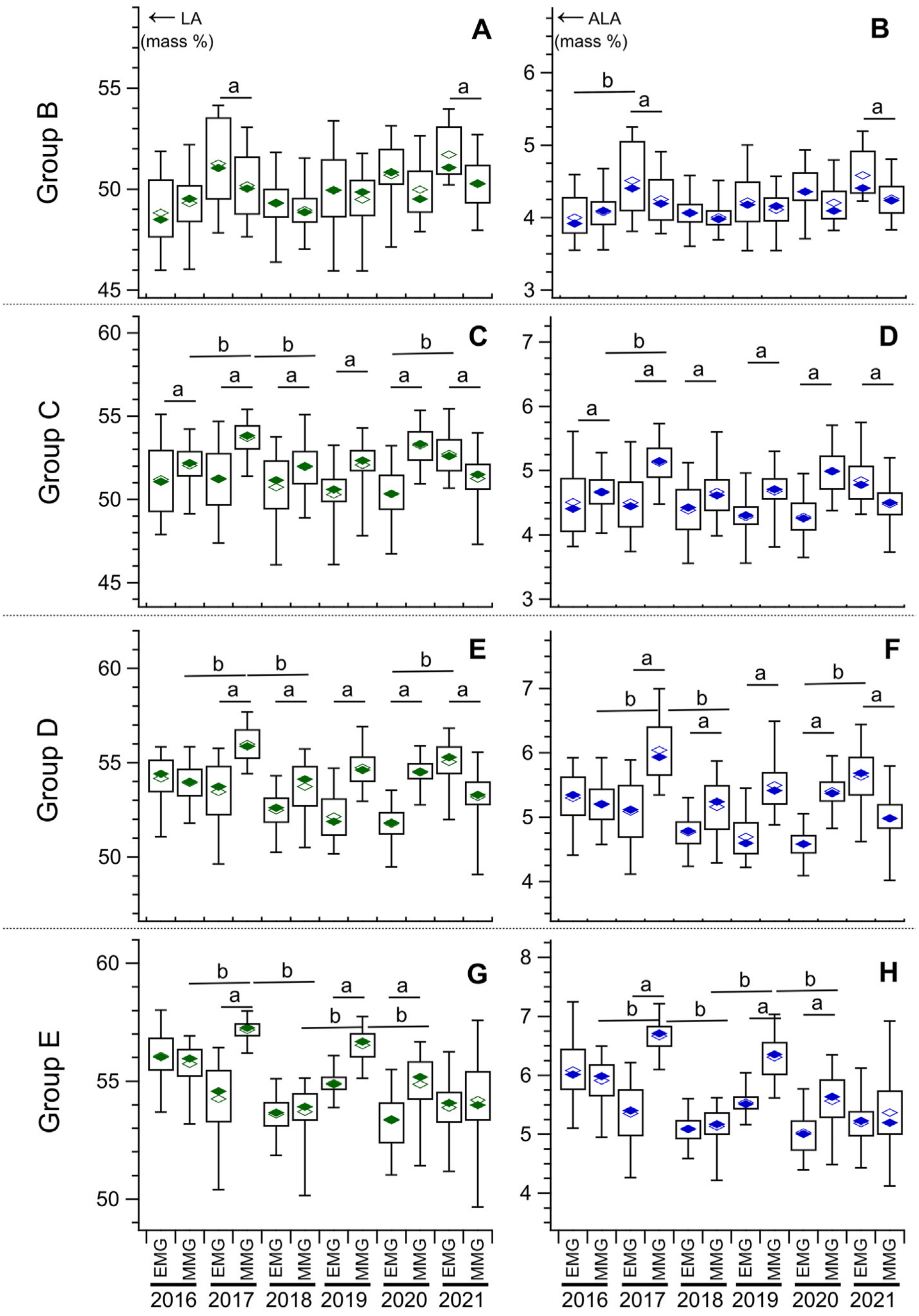


Figure 5. Mean (solid diamond) and median (outline) for the mass percent of LA (left column) and ALA (right column). Box plots show the mean with second and third quartiles; whiskers extend to 2nd and 98th percentiles. Pairs marked **(a)** indicate intrayear differences after Bonferroni correction ($P < 0.001$), and (**b**) indicate interyear differences between groups at the same relative time of year ($P < 0.001$). ALA, α-linolenic acid; EMG, early-maturing group; LA, linoleic acid; MMG, midmaturing group.

variation. Mean daytime high temperatures over the relevant date ranges were used in the composition models.

Weather-based geographic variability

Predicted fatty acid composition based on daily maximum temperature demonstrated increased concentration of LA and ALA at a higher latitude for both EMG and MMG (Figure 4A–D). Counties were grouped by latitude at 5° intervals (Table 3). From South to North, the model predicted increases of 48.1%–55.4% for LA and 3.88%–5.83% for ALA as the temperatures declined. MMG soybeans were predicted to have increased LA and ALA for latitude groups C, D, and E, when compared with EMG soybeans at the same latitude. Each latitude group showed a normal distribution for components (Figure 4E, F). The temperature difference between midsummer (late June–early July) and late summer (August) also impacted the predicted fatty acid composition; cooler August temperatures increased the concentration of LA and ALA. Differences between groups A and B were nonsignificant for LA at either maturity group time point, although significant ($P < 0.001$) differences between maturity groups within the same latitude were evident for both fatty acids in groups E and D.

Composition varied with year as well as with geographic region (Supplementary Figures S3, S4). Cooler August temperatures across the northern plains, upper Midwest, and upstate New York in 2017 and 2019 increased LA and ALA concentrations (Figure 4A–D). Conversely, higher August temperatures in OK and northeast TX decreased LA and ALA content in 2016, 2018, and 2020.

The greatest intrayear variation in fatty acid composition was expected for latitude groups C, D, and E (Figure 5). For most years examined, temperature decreased between July and August, resulting in significantly higher predicted concentrations for PUFA species ($P < 0.001$). The exception was in 2021 for groups C and D, where the PUFA content decreased because of higher August temperatures. Similarly, the 2017 MMG and 2019 MMG periods for group E had significantly higher predicted PUFA content than equivalent periods in the immediately preceding and following years ($P < 0.001$).

Composition of modeled soybean oils

The 3 model soybean oils for the North, Central, and Southern regions are shown in Figure 6, with each point representing a year from 2016 to 2021. Results are reported alongside values from the USDA FDC Foundation Foods data set, with each point representing an analyzed sample [71,72]. The modeled oils from the Central region were significantly higher in LA ($P < 0.05$) than the other modeled oils, whereas those from the South were significantly lower in ALA. The empirical measurements reported in the Foundation Foods data set were higher for ALA than our predicted values for all model oils, although the values for LA overlapped with predicted values for several modeled oils. In nearly all cases, the modeled soybean fatty acid content demonstrated wider variability than the empirical measurements in this dataset.

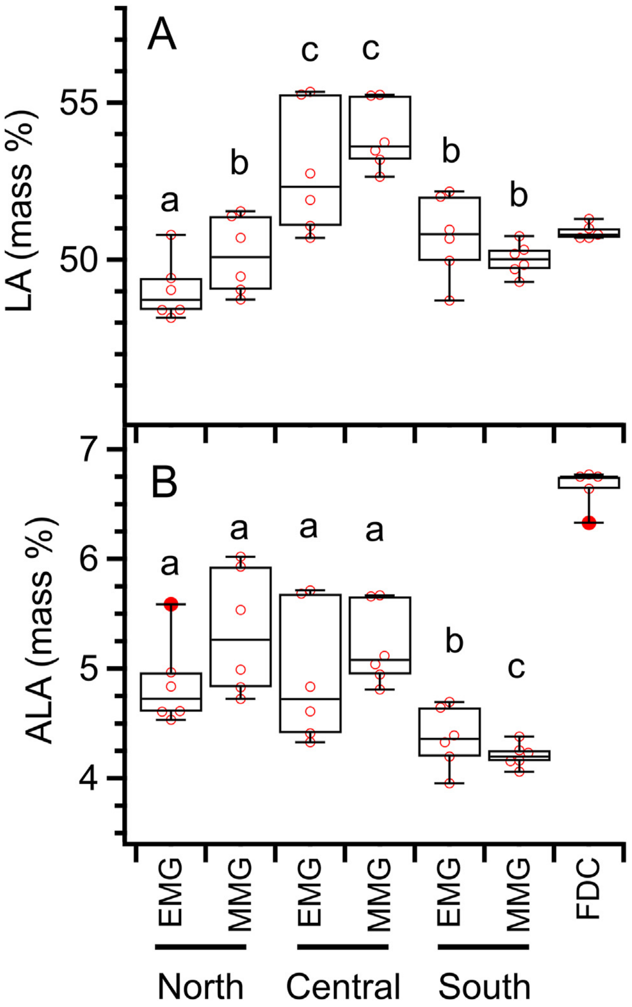


Figure 6. Modeled soybean oil composition based on temperature differences across 3 high-producing regions during 2016–2021 for (A) LA and (B) ALA. FDC compositional values are included in the rightmost column [72]. Box plots show the mean with second and third quartiles; whiskers extend to 2nd and 98th percentiles. Pairs marked **(a)** indicate intrayear differences after Bonferroni correction ($P < 0.001$), outliers outside the 1.5 interquartile range are shown with solid markers. ALA, α-linolenic acid; EMG, early-maturing group; FDC, FoodData Central; LA, linoleic acid; MMG, midmaturing group.

Discussion

To our knowledge, this project is the first study modeling the impact of climate on essential nutrients in a dietary staple, with a clear biochemical link to climate. For >100 y, the USDA has been a global leader in providing food composition data used by consumers, researchers, and private entities worldwide to make informed choices about thousands of foods in the human diet [71]. Values in databases represent a snapshot; composition changes due to genetics, environment, and food system variables are not captured. Given a cost of ~$50, 000 per snapshot [71], assembling a dynamic picture of food composition in response to rapidly changing variables, such as climate, is expensive. Integrating nutrition, plant physiology, and data science makes it possible to highlight where and when nutritionally relevant composition changes should occur, guiding both research activities and potential human health interventions. Soybean oil is ideal for this integrated analysis because soybeans are a well-characterized crop grown globally across temperate, tropical, and subtropical regions [73]. In the United States, soybean oil represents a major source of essential fatty acids in the diet [20], and the biochemical mechanism connecting fatty acid composition with growing temperature is well understood.

Based on the increasing availability of high-OA vegetable oils in the American diet, Raatz et al. [46] used data from the NHANES and the What We Eat In America survey to model the impact of replacing traditional vegetable oils with high-OA variants at 10%, 25%, and 50% replacement in the American diet for 12 adult populations. Their model predicted that a $\geq$25% substitution would result in some age or sex groups not meeting the adequate daily intake levels for ALA, and at 50% replacement, most demographic groups fell short. These replacement levels correspond to an oil containing ALA at concentrations of 5.68% and 4.55%, respectively. Further, when Belury et al. [47] performed a complimentary modeling analysis for populations of children aged 1–8 y, they found that a high-OA substitution rate of 40%, equivalent to an ALA concentration of 5.00% in soybean oil, would result in inadequate daily intake of ALA for all children. The results of our model demonstrate that these thresholds can be readily crossed through increased growth temperature alone, irrespective of the soybean cultivar. Our regional modeled oils showed ALA content of <5.68% for most groups (Figure 6), with ALA concentrations in EMG groups for the North and Central model oils reaching <5.0 %. Our model also reported ALA concentrations of <4.55% for the modeled oil from the South region, irrespective of the maturity group.

Comparing the model output to reported values used by the nutrition community illustrates the importance of performing a broad examination for variability. The USDA FDC Foundation Foods database includes metadata for samples, such as the date and location of sampling, as well as brand information [72]. Of the 4 samples within FDC, 3 are from private-label or store brands (Kroger, Great Value, and Amazon Happy Belly) and 1 represents a name brand (Crisco). These samples were obtained on or about June 20, 2019, and all but 1 were purchased in the Blacksburg or Christiansburg region of VA. As a geographic and temporal snapshot, the measured distribution of LA was much less variable than our model results (Figure 6A). The concentration of ALA in the name-brand oil represents an outlier to the lower side of the distribution (Figure 6B). When Equation *1* was solved for temperature using the mean fatty acid concentrations of LA and ALA from FDC, the model predicted daytime high temperatures of 26.5°C and 24.1°C, respectively. These calculated values fell within the bounds of the confidence intervals in Figure 3 and may be a consequence of more temperate growing conditions, similar to those reported by Carrera et al. [64], although additional metadata are necessary to confirm this hypothesis.

Our work addresses a gap between nutrition and agricultural modeling by providing mathematical functions linking a common model parameter to nutritional outcomes beyond yield. In agriculture, process-based modeling employs functions that describe the contribution of variables, such as nitrogen availability, water, temperature, and photoperiod to predict yield [74]. Temperature is used in these models to describe plant development and growth rate [75,76], and with the addition of the parameters described in Table 2, it is possible to estimate fatty acid composition. Previous modeling studies for fatty acid composition as a function of temperature used geographically limited data sets either from the literature or field studies [33,77,78]. Schulte et al. [79] developed a temperature-responsive model for the fatty acid content of oil seeds, including soybean, from a more limited literature search, with validation based on a field study in KS. They performed a linear regression with 13 data points; however, the resultant model generated negative values for ALA concentration at 40°C. With this larger data set, we could employ a logistic curve that was more representative of biologic processes and allowed extrapolation to include extreme temperatures predicted by some climate projections.

With the data used in our model, microclimate effects within the same latitude are evident. For example, the differences that were predicted for ND, SD, MS, WI, MI, and upstate NY, which share a common latitude but different climate effects due to the proximity to Great Lake. A similar phenomenon was observed empirically by Abdelghany et al. [80] in the analysis of 1025 soybean samples from across China, where samples obtained from temperate highland plateaus of interior China exhibited significantly higher LA content than those obtained from warmer coastal regions, irrespective of the latitude. Building on our work, a more sophisticated model would require higher-resolution data. The frequency and spatial resolution of meteorological data are superior to those of agronomic data. Planting progress data are collected on a statewide basis, resulting in features, such as the discontinuity that sets MO apart from neighboring states (Supplementary Figures S3 and S4). County-level agronomic data would improve the application of our model.

In considering ways to enhance our model, a strategy for collecting additional fatty acid compositional data would greatly improve model accuracy. An excellent example of the quality of data needed is produced by the Canadian Grain Commission for canola [81]. Annually, they analyze approximately 2000 individual and composite samples from 37 census agricultural regions across Canada for several nutritionally relevant components, including fatty acids. Because our purpose in modeling is based on nutrition and the systemic impact of temperature on composition, the model would need the composite fatty acid data and the temperature during seed development within each census agricultural region.

Analogously, soybean and oilseed processing in the United States is regionally distributed primarily east of the Rocky Mountains. Compositional analysis of samples from regional processors would allow for the determination of geospatial variation in the soybean oil supply. Further, because processing occurs year-round, anonymized regional metadata would generate intrayear variability data for fatty acid composition based on temperature. From this information, an improved model assessing the impact of increased daytime high temperatures on the nutritional quality of soybean oil could be constructed. Furthermore, variables, such as increased night-time temperatures, which impact lipid composition in soybeans and other crops, could be included [28,67].

Although our model provides fit parameters for OA and LA, the major human health concern presented was ALA insufficiency, largely because within our model the LA content varied between 30% and 55% over the studied temperature range. This range for LA content is comparable to that of sunflower, safflower, and corn oils, which are alternative dietary sources for LA, although none have ALA content of >2% [82]. Thus, conventionally grown oils provide sufficient LA content, and we believe that an insufficient intake of ALA is more likely a consequence of increasing temperatures. Looking beyond the conventional soybean varieties; however, the growing market for high-OA oils may offer a major challenge for the intake of both essential fatty acids. Oils high in OA and low in PUFA species have been commercially desirable because of increased oxidative stability and long shelf life [83]. To meet this commercial need, breeders have used both transgenic and conventional breeding methods to develop soybean cultivars producing low PUFA concentrations [84,85]. Marketed as having LA and ALA concentrations ≤10% and ≤3%, respectively, these materials are grown and processed within identity-preserved supply chains to prevent mixing with conventional soybeans [86]. This trend toward high-OA oils can also be seen in sunflower and canola oils [87,88]. Given that the incorporation of these high-OA products is predicted to result in ALA insufficiency for large portions of the population [46,47], temperature-based suppression of fatty acid desaturation may also put populations at risk for LA insufficiency. Further research is needed to assess the impact of environmental stressors on the rapidly changing food system.

In conclusion, we determined the potential impact of daytime high temperature on the essential fatty acid content of soybean oil using publicly available data. When applied to the United States soybean crops, our model predicts a decrease in the consumption of essential fatty acids that may be nutritionally significant. The greatest limitation of our model is the low availability of empirical measurements of fatty acid composition with corresponding geographic and agronomic metadata. Our observations are cultivar-independent and with further study both within the United States and internationally, we can derive a broadly applicable global model suitable for use in current and projected climatic regimes.

Author contributions

The author's responsibilities were as follows – MRB: conceived the study, performed the literature review, developed compositional models, managed data, performed analysis, and wrote the manuscript; SG: obtained daytime high-temperature data for model application and contributed to the manuscript. Both authors read and approved the final manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

Funding

This work was supported by the United States Department of Agriculture, Agricultural Research Service projects 8040-52000-066-00D and 8070-66000-001-000D. The United States Department of Agriculture is an equal opportunity provider and employer. Mention of trade names or commercial products in this publication is solely to provide specific information and does not imply recommendation or endorsement by the United States Department of Agriculture.

Data availability

Data described in the manuscript, code book, and analytic code will be made available upon request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ajcnut.2023.08.024.

References

[1] N. Fodor, A. Challinor, I. Droutsas, J. Ramirez-Villegas, F. Zabel, A.K. Koehler, et al., Integrating plant science and crop modeling: assessment of the impact of climate change on soybean and maize production, Plant. Cell. Physiol. 58 (11) (2017) 1833–1847, https://doi.org/10.1093/pcp/pcx141.

[2] B.K. Kogo, L. Kumar, R. Koech, P. Langat, Modelling impacts of climate change on maize (Zea mays L.) growth and productivity: a review of models, outputs and limitations, J. Geosc. Environ. Prot. 7 (8) (2019) 76–95, https://doi.org/10.4236/gep.2019.78006.

[3] R. Raymundo, S. Asseng, D. Cammarano, R. Quiroz, Potato, sweet potato, and yam models for climate change: a review, Field. Crops. Res. 166 (2014) 173–185, https://doi.org/10.1016/j.fcr.2014.06.017.

[4] S.A. Jennings, A.K. Koehler, K.J. Nicklin, C. Deva, S.M. Sait, A.J. Challinor, Global potato yields increase under climate change with adaptation and CO_2 fertilisation, Front. Sustain. Food. Syst. 4 (2020) 1–17, https://doi.org/10.3389/fsufs.2020.519324.

[5] S. Asseng, F. Ewert, C. Rosenzweig, J.W. Jones, J.L. Hatfield, A.C. Ruane, et al., Uncertainty in simulating wheat yields under climate change, Nat. Clim. Change. 3 (9) (2013) 827–832, https://doi.org/10.1038/nclimate1916.

[6] I.K. Dawson, J. Russell, W. Powell, B. Steffenson, W.T.B. Thomas, R. Waugh, Barley: a translational model for adaptation to climate change, New. Phytol. 206 (3) (2015) 913–931, https://doi.org/10.1111/nph.13266.

[7] Y. Assefa, L.C. Purcell, M. Salmeron, S. Naeve, S.N. Casteel, P. Kovács, et al., Assessing variation in US soybean seed composition (protein and oil), Front. Plant. Sci. 10 (2019) 298, https://doi.org/10.3389/fpls.2019.00298.

[8] M.L. Thomey, R.A. Slattery, I.H. Köhler, C.J. Bernacchi, D.R. Ort, Yield response of field-grown soybean exposed to heat waves under current and elevated CO_2, Glob. Chang. Biol. 25 (12) (2019) 4352–4368, https://doi.org/10.1111/gcb.14796.

[9] L. Wei, W. Wang, J. Zhu, Z. Wang, J. Wang, C. Li, et al., Responses of rice qualitative characteristics to elevated carbon dioxide and higher temperature: implications for global nutrition, J. Sci. Food. Agric. 101 (9) (2021) 3854–3861, https://doi.org/10.1002/jsfa.11021.

[10] C. Zhu, K. Kobayashi, I. Loladze, J. Zhu, Q. Jiang, X. Xu, et al., Carbon dioxide (CO_2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries, Sci. Adv. 4 (2018), https://doi.org/10.1126/sciadv.aaq1012 eaaq1012.

[11] L.H. Ziska, C.F. Morris, E.W. Goins, Quantitative and qualitative evaluation of selected wheat varieties released since 1903 to increasing atmospheric carbon dioxide: can yield sensitivity to carbon dioxide be a factor in wheat performance? Glob. Chang. Biol. 10 (10) (2004) 1810–1819, https://doi.org/10.1111/j.1365-2486.2004.00840.x.

[12] U.M. Ruiz-Vera, A.P. De Souza, M.R. Ament, R.M. Gleadow, D.R. Ort, High sink strength prevents photosynthetic down-regulation in cassava grown at elevated CO_2 concentration, J. Exp. Bot. 72 (2) (2021) 542–560, https://doi.org/10.1093/jxb/eraa459.

[13] J. Soares, T. Deuchande, L.M.P. Valente, M. Pintado, M.W. Vasconcelos, Growth and nutritional responses of bean and soybean genotypes to elevated CO_2 in a controlled environment, Plants (Basel). 8 (11) (2019) 465, https://doi.org/10.3390/plants8110465.

[14] J.C. Soares, C.S. Santos, S.M.P. Carvalho, M.M. Pintado, M.W. Vasconcelos, Preserving the nutritional quality of crop plants under a changing climate: importance and strategies, Plant Soil 443 (1-2) (2019) 1–26, https://doi.org/10.1007/s11104-019-04229-0.

[15] I. Loladze, Hidden shift of the ionome of plants exposed to elevated CO_2 depletes minerals at the base of human nutrition, ELife 3 (2014) e02245, https://doi.org/10.7554/elife.02245.

[16] USDA Economic Research Service, Oil crops yearbook [cited August 18, 2023]. Available from: https://www.ers.usda.gov/data-products/oil-crops-yearbook/oil-crops-yearbook/.

[17] USDA Foreign Agricultural Service. Production, supply, and distribution database [cited August 11, 2023], Available from: https://apps.fas.usda.gov/psdonline/app/index.html#/app/advQuery.

[18] E. Meijaard, J.F. Abrams, J.L. Slavin, D. Sheil, Dietary fats, human nutrition and the environment: balance and sustainability, Front. Nutr. 9 (2022) 878644, https://doi.org/10.3389/fnut.2022.878644.

[19] Dietary Guidelines for Americans, 2020–2025, 9th Edition, US Department of Agriculture and US Department of Heath and Human Services, Washington, DC, 2020 [cited August 22, 2022] Available from: http://www.dietaryguidelines.gov/sites/default/files/2020-12/Dietary_Guidelines_for_Americans_2020-2025.pdf.

[20] T.L. Blasbalg, J.R. Hibbeln, C.E. Ramsden, S.F. Majchrzak, R.R. Rawlings, Changes in consumption of omega-3 and omega-6 fatty acids in the United States during the 20th century, Am. J. Clin. Nutr. 93 (5) (2011) 950–962, https://doi.org/10.3945/ajcn.110.006643.

[21] A. Sala-Vila, J. Fleming, P. Kris-Etherton, E. Ros, Impact of α-linolenic acid, the vegetable ω-3 fatty acid, on cardiovascular disease and cognition, Adv. Nutr. 13 (5) (2022) 1584–1602, https://doi.org/10.1093/advances/nmac016.

[22] J.A. Fleming, P.M. Kris-Etherton, The evidence for α-linolenic acid and cardiovascular disease benefits: comparisons with eicosapentaenoic acid and docosahexaenoic acid, Adv. Nutr. 5 (6) (2014) 863S–876S, https://doi.org/10.3945/an.114.005850.

[23] M.S. Farvid, M. Ding, A. Pan, Q. Sun, S.E. Chiuve, L.M. Steffen, et al., Dietary linoleic acid and risk of coronary heart disease: a systematic review and meta-analysis of prospective cohort studies, Circulation 130 (18) (2014) 1568–1578, https://doi.org/10.1161/circulationaha.114.010236.

[24] F. Marangoni, C. Agostoni, C. Borghi, A.L. Catapano, H. Cena, A. Ghiselli, et al., Dietary linoleic acid and human health: focus on cardiovascular and cardiometabolic effects, Atherosclerosis 292 (2020) 90–98, https://doi.org/10.1016/j.atherosclerosis.2019.11.018.

[25] Z. Attia, C.S. Pogoda, S. Reinert, N.C. Kane, B.S. Hulke, Breeding for sustainable oilseed crop yield and quality in a changing climate, Theor. Appl. Genet. 134 (6) (2021) 1817–1827, https://doi.org/10.1007/s00122-021-03770-w.

[26] K. Bilyeu, J.D. Gillman, A.R. Leroy, Novel FAD3 mutant allele combinations produce soybeans containing 1% linolenic acid in the seed oil, Crop. Sci. 51 (1) (2011) 259–264, https://doi.org/10.2135/cropsci2010.01.0044.

[27] K. Bilyeu, L. Palavalli, D. Sleper, P. Beuselinck, Mutations in soybean microsomal omega-3 fatty acid desaturase genes reduce linolenic acid concentration in soybean seeds, Crop. Sci. 45 (5) (2005) 1830–1836, https://doi.org/10.2135/cropsci2004.0632.

[28] S. Narayanan, P.J. Tamura, M.R. Roth, P.V. Prasad, R. Welti, Wheat leaf lipids during heat stress: I. High day and night temperatures result in major lipid alterations, Plant. Cell. Environ. 39 (4) (2016) 787–803, https://doi.org/10.1111/pce.12649.

[29] S. Narayanan, Z.S. Zoong-Lwe, N. Gandhi, R. Welti, B. Fallen, J.R. Smith, et al., Comparative lipidomic analysis reveals heat stress responses of two soybean genotypes differing in temperature sensitivity, Plants 9 (4) (2020) 457, https://doi.org/10.3390/plants9040457.

[30] Z.S. Zoong Lwe, R. Welti, D. Anco, S. Naveed, S. Rustgi, S. Narayanan, Heat stress elicits remodeling in the anther lipidome of peanut, Sci. Rep. 10 (1) (2020) 22163, https://doi.org/10.1038/s41598-020-78695-3.

[31] G.E. Byfield, R.G. Upchurch, Effect of temperature on microsomal omega-3 linoleate desaturase gene expression and linolenic acid content in developing soybean seeds, Crop. Sci. 47 (6) (2007) 2445–2452, https://doi.org/10.2135/CROPSCI2007.05.0263.

[32] T.M. Cheesbrough, Changes in the enzymes for fatty acid synthesis and desaturation during acclimation of developing soybean seeds to altered growth temperature, Plant. Physiol. 90 (2) (1989) 760–764, https://doi.org/10.1104/pp.90.2.760.

[33] R.W. Howell, F.I. Collins, Factors affecting linolenic and linoleic acid content of soybean oil, J. Agron. 49 (11) (1957) 593–597, https://doi.org/10.2134/agronj1957.00021962004900110007x.

[34] W.R. Fehr, C.E. Caviness, Stages of soybean development, Special report 80, Iowa State University, Aimes, IA, 1977.

[35] G.A. Constable, I.A. Rose, Variability of soybean phenology response to temperature, daylength and rate of change in daylength, Field. Crops. Res. 18 (1) (1988) 57–69, https://doi.org/10.1016/0378-4290(88)90059-7.

[36] D.L. Dornbos, M.B. McDonald, Mass and composition of developing soybean seeds at five reproductive growth stages, Crop. Sci. 26 (3) (1986) 624–630, https://doi.org/10.2135/cropsci1986.0011183x002600030042x.

[37] G.E. Byfield, R.G. Upchurch, Effect of temperature on delta-9 stearoyl-acp and microsomal omega-6 desaturase gene expression and fatty acid content in developing soybean seeds, Crop. Sci. 47 (4) (2007) 1698–1704, https://doi.org/10.2135/cropsci2006.04.0213.

[38] S. Mourtzinis, J.E. Specht, S.P. Conley, Defining optimal soybean sowing dates across the US, Sci. Rep. 9 (1) (2019) 2800, https://doi.org/10.1038/s41598-019-38971-3.

[39] S. Kyei-Boahen, L. Zhang, Early-maturing soybean in a wheat–soybean double-crop system yield and net returns, J. Agron. 98 (2) (2006) 295–301, https://doi.org/10.2134/agronj2005.0198.

[40] R.B. Curry, J.W. Jones, K.J. Boote, R.M. Peart, L.H. Allen Jr., N.B. Pickering, Response of soybean to predicted climate change in the USA. Climate change and agriculture: analysis of potential international impacts, ASA Special Publications, 1995, pp. 163–182.

[41] X.Y. Hao, X. Han, H. Ju, E.D. Lin, Impact of climatic change on soybean production: a review, Ying Yong. Sheng. Tai. Xue. Bao. 21 (10) (2010) 2697–2706.

[42] Q. Sun, Y. Zhang, X. Che, S. Chen, Q. Ying, X. Zheng, et al., Coupling process-based crop model and extreme climate indicators with machine learning can improve the predictions and reduce uncertainties of global soybean yields, Agriculture 12 (11) (2022) 1791, https://doi.org/10.3390/agriculture12111791.

[43] H.M.D. Goulart, K. van der Wiel, C. Folberth, E. Boere, B. van den Hurk, Increase of simultaneous soybean failures due to climate change, Earth's Future. 11 (4) (2023) EF003106, https://doi.org/10.1029/2022EF003106.

[44] M. Ejaz, G. Abbas, Z. Fatima, P. Iqbal, M.A. Raza, A.M.S. Kheir, et al., Modelling climate uncertainty and adaptations for soybean-based cropping system, Int. J. Plant. Prod. 16 (2) (2022) 235–250, https://doi.org/10.1007/s42106-022-00190-8.

[45] K. Kothari, R. Battisti, K.J. Boote, S.V. Archontoulis, A. Confalone, J. Constantin, et al., Are soybean models ready for climate change food impact assessments? Eur. J. Agron. 135 (2022) 126482 https://doi.org/10.1016/j.eja.2022.126482.

[46] S.K. Raatz, Z. Conrad, L. Jahns, M.A. Belury, M.J. Picklo, Modeled replacement of traditional soybean and canola oil with high-oleic varieties increases monounsaturated fatty acid and reduces both saturated fatty acid and polyunsaturated fatty acid intake in the US adult population, Am. J. Clin. Nutr. 108 (3) (2018) 594–602, https://doi.org/10.1093/ajcn/nqy127.

[47] M.A. Belury, S. Raatz, Z. Conrad, Modeled substitution of traditional oils with high–oleic acid oils decreases essential fatty acid intake in children, Am. J. Clin. Nutr. 115 (4) (2022) 1180–1188, https://doi.org/10.1093/ajcn/nqab407.

[48] A.C. Tricco, E. Lillie, W. Zarin, K.K. O'Brien, H. Colquhoun, D. Levac, et al., PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation, Ann. Intern. Med. 169 (7) (2018) 467–473.

[49] USDA National Agricultural Statistics Service Quick Stats, USDA National Agricultural Statistics Service, Washington, DC, [cited July 2022]. Available from: https://quickstats.nass.usda.gov/.

[50] US Soybean Export Council, Conversion Table [cited January 31 , 2023]. Available from: https://ussec.org/resources/conversion-table/.

[51] J.T. Abatzoglou, Development of gridded surface meteorological data for ecological applications and modelling, Int. J. Climatol. 33 (1) (2013) 121–131, https://doi.org/10.1002/joc.3413.

[52] USDA National Agricultural Statistics Service, Cropland Data Layer (2008–2021) [Internet] Available from: https://nassgeodata.gmu.edu/CropScape, 2022.

[53] R.J. Hijmans, Raster: geographic data analysis and modeling, R package version 3, 2022, pp. 6–11.

[54] R Core Team, R: a language and environment for statistical computing [Internet], R Foundation for Statistical Computing, Vienna, Austria, 2022 [cited August 2023] Available from: https://www.R-project.org/.

[55] Soybean Meal INFO center-Processors, [Internet]. 2023 [cited March 1, 2023]. Available from: https://www.soymeal.org/processors/.

[56] H. Wickham, M. Averick, J. Bryan, W. Chang, L. McGowan, R. François, et al., Welcome to the tidyverse, J. Open. Source. Softw. 4 (43) (2019) 1686, https://doi.org/10.21105/joss.01686.

[57] B.D. Rennie, J. Zilka, M.M. Cramer, W.D. Beversdorf, Genetic analysis of low linolenic acid levels in the soybean line PI 361088B, Crop. Sci. 28 (4) (1988) 655–657, https://doi.org/10.2135/cropsci1988.0011183x002800040019x.

[58] B.D. Rennie, J.W. Tanner, Fatty acid composition of oil from soybean seeds grown at extreme temperatures, J. Am. Oil. Chem. Soc. 66 (11) (1989) 1622–1624, https://doi.org/10.1007/bf02636189.

[59] R.B. Wolf, J.F. Cavins, R. Kleiman, L.T. Black, Effect of temperature on soybean seed constituents: oil, protein, moisture, fatty acids, amino acids and sugars, J. Am. Oil. Chem. Soc. 59 (5) (1982) 230–232, https://doi.org/10.1007/bf02582182.

[60] D.L. Dornbos, R.E. Mullen, Soybean seed protein and oil contents and fatty acid composition adjustments by drought and temperature, J. Am. Oil. Chem. Soc. 69 (3) (1992) 228–231, https://doi.org/10.1007/bf02635891.

[61] D.M. Maestri, D.O. Labuckas, J.M. Meriles, A.L. Lamarque, J.A. Zygadlo, C.A. Guzmán, Seed composition of soybean cultivars evaluated in different environmental regions, J. Sci. Food. Agric. 77 (4) (1998) 494–498, https://doi.org/10.1002/(SICI)1097-0010(199808)77:4<494::AID-JSFA69>3.0.CO;2-B.

[62] S.R. Schnebly, W.R. Fehr, Effect of years and planting dates on fatty acid composition of soybean genotypes, Crop. Sci. 33 (4) (1993) 716–719, https://doi.org/10.2135/cropsci1993.0011183x003300040016x.

[63] E.P. Heppard, A.J. Kinney, K.L. Stecca, G.H. Miao, Developmental and growth temperature regulation of two different microsomal omega-6 desaturase genes in soybeans, Plant Physiol 110 (1) (1996) 311–319, https://doi.org/10.1104/pp.110.1.311.

[64] C. Carrera, M.J. Martínez, J. Dardanelli, M. Balzarini, Environmental variation and correlation of seed components in nontransgenic soybeans: protein, oil, unsaturated fatty acids, tocopherols, and isoflavones, Crop. Sci. 51 (2) (2011) 800–809, https://doi.org/10.2135/cropsci2010.06.0314.

[65] J. Gao, X. Hao, K.D. Thelen, G.P. Robertson, Agronomic management system and precipitation effects on soybean oil and fatty acid profiles, Crop. Sci. 49 (3) (2009) 1049–1057, https://doi.org/10.2135/cropsci2008.08.0497.

[66] N. Bellaloui, A. Mengistu, M.A. Kassem, Effects of genetics and environment on fatty acid stability in soybean seed, Food. Nutr. Sci. 4 (9) (2013) 165–175, https://doi.org/10.4236/fns.2013.49a1024.

[67] L.R. Gibson, R.E. Mullen, Soybean seed composition under high day and night growth temperatures, J. Am. Oil. Chem. Soc. 73 (6) (1996) 733–737, https://doi.org/10.1007/bf02517949.

[68] R.F. Wilson, Seed composition, in: R.H. Boerma, J.E. Specht (Eds.), Soybeans: improvement, production, and uses, Third Edition, American Society of Agronomy, Inc.; Crop Science Society of America, Inc.; Soil Science Society of America, Inc., Madison, WI, 2004, pp. 621–678.

[69] G. Hou, G.R. Ablett, K.P. Pauls, I. Rajcan, Environmental effects on fatty acid levels in soybean seed oil, J. Am. Oil. Chem. Soc. 83 (9) (2006) 759–763, https://doi.org/10.1007/s11746-006-5011-4.

[70] C. Ren, K.D. Bilyeu, P.R. Beuselinck, Composition, vigor, and proteome of mature soybean seeds developed under high temperature, Crop. Sci. 49 (3) (2009) 1010–1022, https://doi.org/10.2135/cropsci2008.05.0247.

[71] N.K. Fukagawa, K. McKillop, P.R. Pehrsson, A. Moshfegh, J. Harnly, J. Finley, USDA's FoodData Central: what is it and why is it needed today? Am. J. Clin. Nutr. 115 (3) (2022) 619–624, https://doi.org/10.1093/ajcn/nqab397.

[72] US Department of Agriculture, Agricultural Research Service [Internet], Food Data Central 2022 (2023) [cited February 1, 2023]. Available from: https://fdc.nal.usda.gov/.

[73] P.D. Goldsmith, in: L.A. Johnson, P.J. White, R. Galloway (Eds.), Economics of soybean production, marketing, and utilization, Soybeans, AOCS Press, 2008, pp. 117–150.

[74] A. Soltani, T. Sinclair, A model for potential production, CABI International, 2012, pp. 140–160.

[75] A. Soltani, T. Sinclair, Phenology - temperature, CABI International, 2012, pp. 55–72.

[76] A. Soltani, T. Sinclair, Phenology - temperature and photoperiod, CABI International, 2012, pp. 73–88.

[77] J.H. Cherry, L. Bishop, M.P. Hasegawa, H.R. Lefflert, Differences in the fatty acid composition of soybean seed produced in northern and southern areas of the, U.S.A., Phytochemistry 24 (2) (1985) 237–241, https://doi.org/10.1016/s0031-9422(00)83527-x.

[78] F.A. Alsajri, C. Wijewardana, J.T. Irby, N. Bellaloui, L.J. Krutz, B. Golden, et al., Developing functional relationships between temperature and soybean yield and seed quality, J. Agron. 112 (1) (2020) 194–204, https://doi.org/10.1002/agj2.20034.

[79] L.R. Schulte, T. Ballard, T. Samarakoon, L. Yao, P. Vadlani, S. Staggenborg, et al., Increased growing temperature reduces content of polyunsaturated fatty acids in four oilseed crops, Ind. Crops. Prod. 51 (2013) 212–219, https://doi.org/10.1016/j.indcrop.2013.08.075.

[80] A.M. Abdelghany, S. Zhang, M. Azam, A.S. Shaibu, Y. Feng, Y. Li, et al., Profiling of seed fatty acid composition in 1025 Chinese soybean accessions from diverse ecoregions, Crop. J. 8 (4) (2020) 635–644, https://doi.org/10.1016/j.cj.2019.11.002.

[81] Canadian Grain Commission Grain Research Laboratory, Scientific analysis of western Canadian canola harvest and export quality [Internet], Canadian Grain

Commission Grain Research Laboratory, Winnipeg, Mannitoba, Canada, 2023 [cited February 1, 2023]. Available from: https://www.grainscanada.gc.ca/en/grain-research/export-quality/oilseeds/canola/.

[82] Joint FAO/WHO Codex Alimentarius Comission, Codex Alimentarius: CXS 210-1999 Standard for Named Vegetable Oils [cited: August 2023]. Available from: https://www.fao.org/input/download/standards/336/CXS_210e_2015.pdf.

[83] S. Knowlton, High-oleic soybean oil, in: F.J. Flider (Ed.), High oleic oils, AOCS Press, Urbana, IL, 2022, pp. 53–87.

[84] K. Bilyeu, J.G. Shannon, J.-D. Lee, T. Pham, inventors; The Curators of the University of Missouri, Columbia, MO, United States, The United States of America, as Represented by the Secretary of Agriculture, Washington, DC (US), Method to Develop High Oleic Acid Soybeans Using Conventional Soybean Breeding Techniques, assignee, 2019. United States of America patent US 10,329,576 B2.

[85] J.J. Fillatti, G.E. Keithly, T. Voelker, T. Ulmasov, inventors, Monsanto Technology, LLC, assignee. Soybean Seed and Oil Compositions and Methods of Making Same, 2007. United States of America patent US 2007/0214516 A1.

[86] R. Sanders, D. Tegeder, U.S., high oleic soybeans & high oleic soybean oil sourcing guide for international customers [cited August 2023], U.S. Soybean Export Council, 2021. Available from: https://ussec.org/u-s-high-oleic-soybeans-high-oleic-soybean-oil-sourcing-guide/.

[87] N.T. Dunford, E. Martínez-Force, J.J. Salas, High-oleic sunflower seed oil, in: F.J. Flider (Ed.), High oleic oils, AOCS Press, Urbana, IL, 2022, pp. 109–124.

[88] M.N.A. Eskin, D.R. Iassonova, C.B. Rempel, High-oleic canola oil, in: F.J. Flider (Ed.), High oleic oils, AOCS Press, Urbana, IL, 2022, pp. 89–108.