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Environmental, nutritional and social assessment of nuts

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Abstract

Nuts are considered an important protein source in sustainable dietary patterns but are seldom studied in detail. Here a multi-criteria decision analysis was used to rank 10 nuts and seeds against 11 environmental, nutritional, and social criteria and provide greater insight into the sustainability impacts of this food group. Weights were defined based on correlation and variance between indicator values, and values were aggregated with a partially non-compensatory method. Several sensitivity analyses tested various sources of uncertainty through the use of country-level data, the use of a fully compensatory aggregation method, and changes to criteria weights. Walnuts and sunflower seeds performed consistently well across sustainability criteria and were ranked in the top two positions in the baseline assessment and most sensitivity analyses. In contrast, cashews performed relatively poorly across most criteria, and were ranked last. Dietary shifts in favor of more sustainable nuts can improve the overall environmental, nutritional and social impacts of nut production and consumption by an average of 23%. Although increasing consumption of walnuts and sunflower seeds may lead to improved sustainability outcomes for total global nut consumption, more research is needed to deepen the understanding of the complex socio-economic factors impacting nut and seed sustainability. The social risk assessment method used in this study can also inform future social impact measurement methods for other food groups.

Keywords Multi-criteria decision analysis · Seeds · Impact assessment · Labor · Nutritional index · Environmental sustainability

Introduction

A dietary transition to predominantly plant-based diets can have beneficial environmental and health impacts (Clark et al. 2019; Springmann et al. 2016; Tilman and Clark 2014), and increased consumption of fruits and vegetables and plant-based protein sources such as nuts are encouraged by national dietary recommendations (Behrens et al. 2017). Nuts are an important component of sustainable diets, with a 42 g d⁻¹ serving providing over 10% of the suggested daily intake of protein, fiber, and several vitamins and minerals (King et al. 2008). Because of the nutrient density of nuts

and seeds, the EAT-Lancet Diet for Planetary Health has recommended a daily per capita intake of 25 g each of peanuts and tree nuts (Willett et al. 2019), which may require an increase of 7 to 11 times current global production (Vanham et al. 2020). Identifying a sustainable mix of nut types to meet these recommendations can contribute to a sustainable dietary transition.

Nuts are generally analyzed as a single food group in sustainable diet studies (Clark et al. 2019; Masset et al. 2014; Nemecek et al. 2016; Paris et al. 2021; Scherer et al. 2019; Tilman and Clark 2014; Willett et al. 2019), which conceals variation between nut types. Nutritional composition across nuts can vary considerably (Brufau et al. 2006; Sokolow et al. 2019). Improvements in the overall impact of global nut consumption may exist as large ranges are present in the water (Pfister et al. 2011; Sokolow et al. 2019; Vanham et al. 2020) and carbon (Clune et al. 2017) footprints of individual nut varieties. In the few cases where nut and seed impacts are individually presented, nuts and seeds have been found to exhibit variation within and trade-offs between water use types (Vanham et al. 2020), several

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environmental dimensions (Karlsson Potter and Rööös 2021; Pfister et al. 2011), and nutrition and environmental dimensions (Sokolow et al. 2019). From these studies, some nuance within the nut food group and trade-offs between impact categories become evident. The variation among known hotspots for the nut food group indicates a potential to emphasize better-performing nut varieties to fulfill the shortfall in consumption recommendations for plant-based diets.

As global visions of sustainable food systems include environmental, nutritional, and socio-economic dimensions (FAO 2012), a scope limited to a single environmental indicator or excluding social sustainability may obscure important trade-offs. Future assessments of sustainable food systems should strive for an integrated and multidimensional approach (Green et al. 2020; Jones et al. 2016). Multidimensional indicator sets have been developed by expert working groups and operationalized into holistic indicator sets to measure overall food system performance in individual countries (Gustafson et al. 2016). Other recent efforts to evaluate dietary patterns by assessing individual foods on multidimensional indicators either omit a key sustainability component such as socio-economic impact (Stylianou et al. 2021) or assess foods such as nuts in aggregate (Chen et al. 2019). Multi-indicator studies also typically present disaggregated performance across indicators or use a simple average to create an overall score, which can make interpretation challenging and conceal synergies or trade-offs between indicators. A multidimensional food sustainability assessment model that is sufficiently detailed to address disaggregated agricultural products at the global and country level can contribute to the ongoing research efforts towards evaluating sustainable food systems.

In this study, we develop an assessment model capable of evaluating the sustainability performance of foods on environmental, nutritional and social sustainability indicators, and apply it here to an important but under-researched food group, nuts and seeds. Assessing nuts and seeds on overall sustainability performance can inform production and consumption initiatives for more sustainable diets. A detailed evaluation of different dimensions and the interactions between them can also help producers and consumers identify hotspots and address potential adverse impacts. The social assessment model developed here also provides a basis for future research on social risk evaluation in agricultural supply chains. While we provide the results to make a choice among the nuts, we leave this final interpretation to the reader and user of our results.

In the following sections, we describe the selection of representative indicators for each dimension, data collection and model construction (Sect. [Materials and methods](#)), compare the sustainability performance of nuts from multiple perspectives (Sect. [Results](#)), and reflect on our sustainability

framework as well as the relevance of our findings about nuts (Sect. [Discussion](#)).

Materials and methods

Framework for environmental, nutritional and social assessment

Multi-criteria decision analysis (MCDA), a method for evaluating alternatives against relevant criteria, is useful in contexts where performance must be evaluated on multiple sustainability dimensions, such as environmental, social, and economic (Zanghelini et al. 2018) (see Guitouni and Martel (1998) for an overview of common MCDA methods). MCDA application has increased within the environmental science field over the past few decades (Huang et al. 2011). Life Cycle Assessment (LCA), frequently used for sustainability assessment of food systems, presents information on potential life cycle impacts of alternatives without an explicit normative framework for decision-making between alternatives or impact categories. MCDA complements LCA by allowing results to be interpreted by relative comparison within a decision context (De Luca et al. 2017; Linkov and Seager 2011). Even in the absence of an explicit decision context, such as in the case of some composite indicators designed for a broad audience, MCDA can be used to facilitate an understanding of trade-offs between alternatives and communicate complex concepts (Nardo et al. 2008).

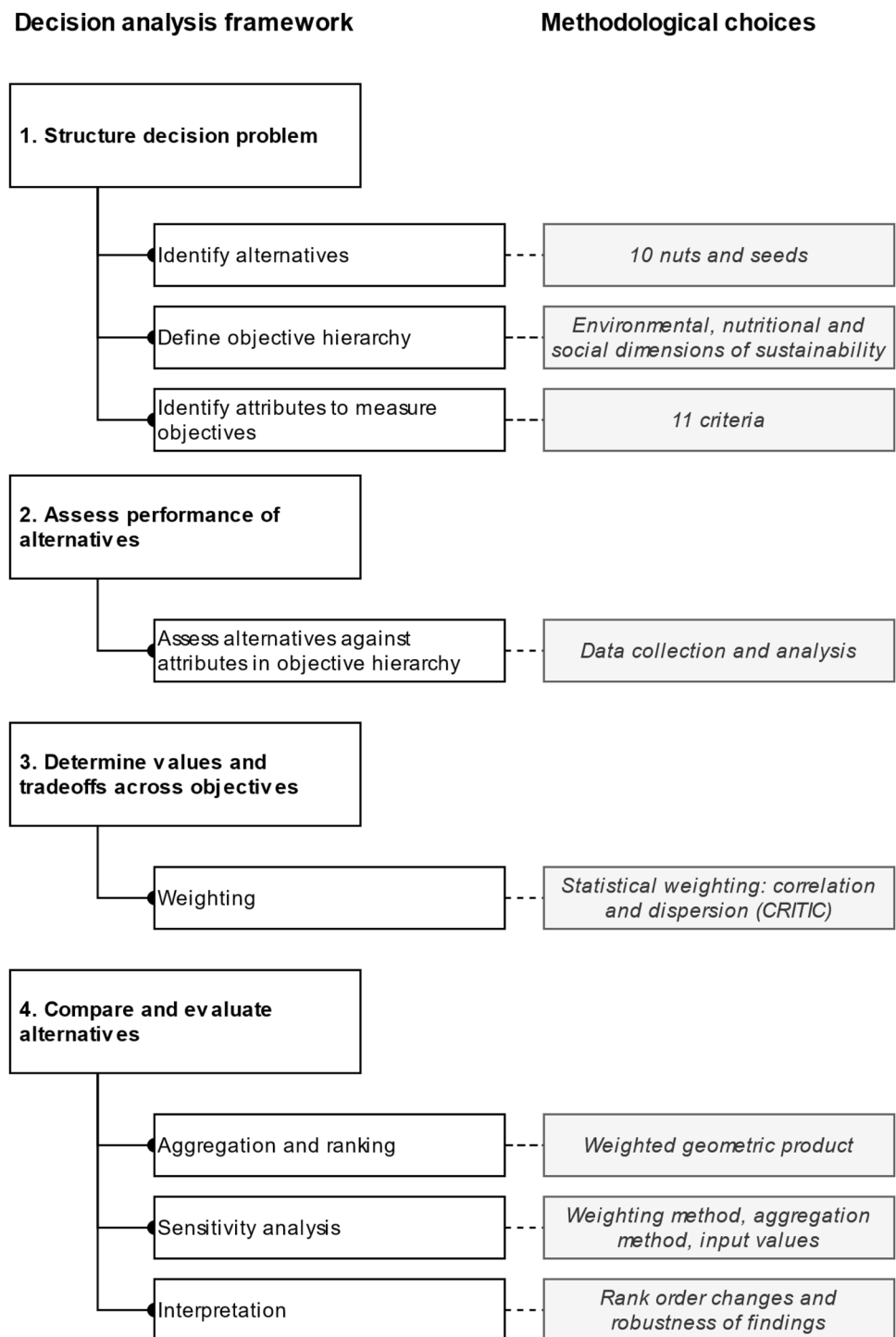
We constructed an MCDA model to assess the environmental, nutritional and social sustainability of different types of nuts and seeds. MCDA allowed for the evaluation of different aspects of production and consumption in a comparative ranking based on a composite weighted score for each alternative that represents the extent to which sustainability was achieved. Four steps constitute an MCDA process: (1) structure the decision problem, (2) assess impacts of alternatives, (3) determine values and trade-offs across objectives, and (4) compare and evaluate alternatives (Keeney 1982). Figure 1 summarizes this process and the corresponding steps in this study.

Structuring the decision problem

Identifying alternatives: selection of nut and seed types

We selected ten nut and seed varieties for analysis based on relevance and data availability in FAOSTAT (FAO 2021) (Supplementary Table S1). Besides botanical nuts (chestnuts and hazelnuts), we also included crops classified as nuts due to their dietary or culinary function. For brevity, the

Fig. 1 Overview of MCDA process and corresponding methodological steps in this study



collective group ‘nuts’ refers to both nuts and seeds, with specific items named where relevant.

Defining objective hierarchy for nut and seed sustainability

To create the decision model, a multidimensional framework for sustainable food systems was translated into an objective hierarchy. An objective hierarchy operationalizes

the decision model by representing the degree to which an overall value (here sustainability) is fulfilled through an ordered set of indicators and sub-indicators (Keeney and Raiffa 1993). We used the three dimensions of sustainable diets proposed by Jones et al. (2016) based on a systematic review and the FAO’s Framework for Sustainable Food Systems (FAO 2012): environmental, nutritional, and social. Although economic indicators are important for measuring

sustainable diets, economic indicators were excluded here due to a lack of consumer prices and complementary economic indicators for nuts in a majority of countries.

Indicators to measure environmental, nutritional, and social dimensions

We chose 11 environmental, nutritional and social indicators based on relevance to a wide audience, appropriateness for nut production and consumption, and data quality and availability (Table 1). Impact categories and indicators were selected at the midpoint level, as these midpoint characterization methods tend to have greater certainty compared to the more complex endpoint categories, such as human health and biodiversity (Hauschild et al. 2013). Indicator development based on these criteria is described in the following

sections (see Supplementary Information (SI) Sect. 1 for further detail).

Environmental indicators A few concepts dominate the environmental dimension of sustainable diets. Greenhouse gas (GHG) emissions are most common, followed by land use, energy use, and water use (Jones et al. 2016). These indicators are also referenced in the EAT-Lancet Diet for Planetary Health (Willett et al. 2019). Furthermore, these indicators reflect issues of global relevance, as climate change, water scarcity and land use were assessed as the most important environmental impacts for food security based on global expert consensus (Scherer et al. 2019). Performance across environmental indicators is not necessarily correlated and can even be inversely related for products of the same food group (Poore and Nemecek

Table 1 Environmental, nutritional and social indicators selected for the MCDA model

Impact category	Indicator	Unit	Data source	SI Reference Section
Climate change	Greenhouse gas emissions (GHG)	kg CO ₂ -eq	Poore and Nemecek (2018)	1.3.1
Land use	Land stress weighted footprint (LSFP)	m ² yr-eq	Pfister et al. (2011) FAO (2021) Haberl et al. (2007)	1.3.2
Water use	Water scarcity weighted footprint (WSFP)	m ³ -eq	Pfister and Bayer (2014) Pfister et al. (2011) Pfister et al. (2009) Mekonnen and Hoekstra (2011)	1.3.3
Nutritional quantity	Nutrient Rich Foods (NRF) Index	[-]	USDA Agricultural Research Service (2019)	1.4.1
Nutritional context	Dietary-dependent Nutritional Quality Index (NQI)	[-]	USDA Agricultural Research Service (2019) Beal et al. (2017) Micha et al. (2014)	1.4.2
Child labor	Children (5–17) ^a involved in economic activity	%	International Labour Organization Department of Statistics (2020) [ILOSTAT hereafter]	1.5
Forced labor	Forced labor	Prevalence per 1 000 workers	Walk Free Foundation (2018) International Labour Organization and Walk Free Foundation (2017)	1.5
Working poverty	Working poverty rate: percentage of employed living below US\$1.90 PPP	%	ILOSTAT (2020)	1.5
Labor rights	Workers not covered by collective bargaining agreements	%	ILOSTAT (2020)	1.5
Labor rights	Workers in the agriculture sector in informal employment	%	ILOSTAT (2020)	1.5
Labor rights	National compliance with fundamental labor rights (collective bargaining and freedom of association)	0–10	ILOSTAT (2020)	1.5
Gender gap	Gender leadership gap	[-]	ILOSTAT (2020)	1.5
Gender gap	Gender pay gap	[-]	ILOSTAT (2020)	1.5
Work safety	Fatal occupational injuries	Incidence per 100 000 workers	ILOSTAT (2020)	1.5
Work safety	Non-fatal occupational injuries	Incidence per 100 000 workers	ILOSTAT (2020)	1.5

^aChildren (5–14) reported in countries with a legal working age of 15

2018). Given the relationship between existing environmental indicators and constraints for attribute selection, three indicators were chosen: carbon footprint, measured by carbon dioxide equivalent (CO₂-eq) emissions of greenhouse gases, land use, characterized by land stress, and water use, characterized by water scarcity (SI Sect. 1.3).

Nutrition indicators Assessing the nutritional content of foods is most commonly approached from the perspective of nutrient quantity, which is measured by nutrient profiling models that evaluate the nutrient content of foods compared to dietary intake recommendations (Green et al. 2020). The Nutrient Rich Foods (NRF) index is frequently used to assess the nutrient quantity of foods (Fulgoni III et al. 2009). This method and similar nutrient indices are based around macronutrients, vitamins and minerals, which are then categorized into qualifying nutrients (nutrients to encourage due to health benefits or deficiency in the general population) and disqualifying nutrients (health-depleting nutrients to be minimized) (Drewnowski and Fulgoni III 2008). In the NRF model, nutrients present in a defined quantity of food are scored against the recommended nutrient intake (RNI) values, which are then averaged or added together to create a single comparable score. Dietary context can also influence the potential nutritional value of a specific food (Hallström et al. 2018). Sonesson et al. (2019) propose the dietary-dependent Nutrient Quality Index (NQI) indicator to account for the consumption ratio of nutrients in a diet by assigning higher or lower weights to nutrients lacking or consumed in excess in reference diets. To evaluate nutrients within heterogeneous global diets, we used the NRF index and the complementary NQI method.

Social indicators The current landscape for social sustainability measurement has not yet coalesced into a unified approach with a shared theoretical framework (Kühnen and Hahn 2018). Nevertheless, some common themes emerge, as approximately half of existing studies reference human rights and working conditions (Janker and Mann 2020). Social Life Cycle Assessment (S-LCA) is one of the major methods for evaluating the social impact of a product or service, but S-LCA is still relatively new; the method has only converged on a defined framework since 2006 (Dreyer et al. 2006) and guidelines since 2009 (United Nations Environment Programme 2009). Social impact can be measured in multiple ways, including social footprint (overall positive and negative impact), social handprint (positive impact) and social risk, among others (United Nations Environment Programme 2020). Social risk in an S-LCA analysis refers to the potential for adverse social impact (United Nations Environment Programme 2020), although this only refers to the relative likelihood of an impact and not the severity

and likelihood of a phenomenon as in traditional risk assessment.

We adapted the S-LCA principles to quantify social risk linked to a specific production country. Based on its frequency of use within social impact literature (Janker and Mann 2020), we selected the stakeholder category *Workers* as the most salient stakeholder group for analysis. The 11 impact subcategories relevant for workers presented in the S-LCA guidelines served as a starting point for indicator development (United Nations Environment Programme 2020, p. 23) (Table S6). Impact categories were cross-referenced against the Sustainable Development Goals (SDGs) to identify the most material impact categories and explore potential indicators. Impact category selection and indicator definition was an iterative process, as an impact category was eliminated if no quantitative indicator could be identified to operationalize the impact category. We identified child labor, forced labor, labor rights, and working conditions (occupational health and safety) through this approach. Working poverty was identified as a proxy indicator for fair salary and was included as an impact category due to its link with SDG target 1.1. Informed by Xiao et al. (2017) and Simas et al. (2014), gender equality was included and served as a proxy for equal opportunities and non-discrimination.

Measuring performance of alternatives against defined sustainability criteria

For indicators across the three dimensions, the functional unit for analysis was 50 g raw (unroasted) shelled-equivalent product at the farm gate. The system boundary includes impacts from cultivation, harvest, and pre-processing (e.g., drying and grading). We omit post-farm gate impacts, as these often constitute a small share of the overall impacts of food products (Tilman and Clark 2014), and we expect there to be less variation among nuts, making it less relevant for a relative comparison.

Indicators were calculated for each crop-country producer pairing identified within the FAO production analysis (SI Sect. 2.1.). Data were collected at the country level to test the applicability of this method at both country and global scales (Table 1). In the case of social indicators, the values were collected at the country level independent of nut variety due to limited data availability of labor inputs specific to each nut (SI Sect. 1.5). Nutrient quantities were assumed to be properties independent of production context and were collected for each nut. Global weighted averages were calculated for each indicator from country-level indicator values and the production of each nut per country (or population, in the case of NQI), except for NRF.

We attributed all impacts to nut kernels rather than allocating a partial burden to co-products such as hulls and woody biomass. The allocation of co-products can impact

the overall environmental footprint of nut products (Brito de Figueirêdo et al. 2016), as co-products can be used in electricity production (Marvinney and Kendall 2021) or industrial applications (Lin et al. 2013; Rojas-Bringas et al. 2021). Applying economic allocation for co-products would decrease the relative environmental burden of nut kernels, especially for nuts with lower economic value relative to co-products.

Determining values and trade-offs across objectives

Weighting approach

Weighting refers to the process that assigns a ratio representing either the level of importance or the degree of permissible trade-off to each criterion in the decision model. We used statistical methods to define indicator weights for the baseline scenario and sensitivity analyses. Although participatory weighting methods are more common (Cinelli et al. 2020), statistical weighting methods offer a transparent and reproducible method for determining weights in the absence of stakeholder input. Together with the aggregation method, statistically derived weights determine the trade-off ratios between indicators.

We chose the CRITERIA Importance Through Inter-criteria Correlation (CRITIC) technique as the baseline statistical weighting method. CRITIC uses features of the dataset to calculate weights by combining a measure of intra-indicator variance (standard deviation) with inter-criteria variance (measured by correlation coefficient, here Spearman rank correlation) (Diakoulaki et al. 1995). This method performs similarly to principal component analysis for representation of contrast intensity within criteria and correlation between indicators but is more transparent because interpreting rotation and load coefficients is not required (Diakoulaki et al. 1995). As a weighting technique that derives weights from basic statistical properties of the dataset without requiring stakeholder input, CRITIC was well-suited for this study, although limitations exist (see SI Sect. 1.7.3). We calculated weights within and across dimensions in a two-step process, using a normalized performance matrix each time.

Normalization

When criteria have different units and scales, normalization of the performance matrix to a common scale is necessary to ensure comparable weights and aggregated scores. Min–max normalization is the most common normalization method and involves scaling each criterion to the interval [0,1] by subtracting the minimum criterion value from each data point before dividing by the range (Nardo et al. 2008) (Eq. 1).

$$s_n = \frac{x - \min(S)}{\max(S) - \min(S)} \quad (1)$$

where s_n is the normalized score for an item x from set S .

Geometric aggregation requires positive values and is incompatible with min–max normalization (Talukder et al. 2017). After min–max normalization, social and environmental indicators were reoriented towards maximization by subtracting values from one. All values were then rescaled to the interval [0.01, 1] to permit both linear and geometric aggregation methods. Normalization was repeated before each aggregation step, and the same normalization procedure was repeated for both the global and country level datasets.

Evaluating alternatives against decision criteria

Aggregation and ranking

The rank order is determined based on the final aggregated score of all indicators, which represents the extent to which the main objective in the hierarchy is fulfilled. We preferred a model where alternatives with balanced performance and synergies among criteria would perform better than alternatives with erratic performance and large trade-offs. Two major types of aggregation models exist: compensatory and non-compensatory (Guitouni and Martel 1998). The degree to which performance on one indicator can compensate for performance on another indicator influences the interpretation of weights. With statistically derived weights, (partially) compensatory aggregation methods allow weights to represent the degree of substitutability between performance on one criterion with respect to another (Nardo et al. 2008). The partially compensatory weighted geometric product aggregation method outperforms the fully compensatory linear weighted sum on measures of information loss as more relative contrast is conveyed in the final score (Zhou et al. 2006, 2010). Geometric aggregation is widely accepted within MCDA and guards against some compensability between dimensions by penalizing extremely poor performance (Greco et al. 2019). With the weighted geometric product, trade-off ratios between indicators increase as performance disparity increases so that very poor performance requires a larger absolute improvement to compensate.

Following the goal of the decision model, we used the weighted geometric product as the baseline aggregation method to reflect a partial degree of compensability so that inconsistent performance was reflected in the final score and rank order (Eq. 2). Linear aggregation (linear weighted sum) was tested in a sensitivity analysis (Eq. 3).

$$A_i^{GM} = \prod_{j=1}^m x_j^{w_j} \text{ for } m \text{ criteria} \quad (2)$$

$$A_i^{WS} = \sum_{j=1}^m x_j w_j \text{ for } m \text{ criteria} \quad (3)$$

Weighting and aggregation took place in two steps: within each dimension and between the environmental, nutritional and social dimensions. The total aggregate scores for each alternative ranged from 0 to 1 and rank order was determined from best (1) to worst (0) score.

Sensitivity analysis

A sensitivity analysis tests the robustness of the decision model results to various methodological choices and input parameters, typically measured by rank reversal in the highest ranks, or a general measure of rank change across all alternatives. We conducted several sensitivity analyses on the indicator input values, criteria weights, and aggregation methods (Table S9). No sensitivity analysis was performed on the normalization method due to minimal expected influence on final ranks and the limited quantity of techniques compatible with geometric aggregation.

The average rank shift of each alternative (i) resulting from each sensitivity analysis (SA) in reference to the baseline (ref) was calculated for m alternatives:

$$\overline{\Delta Rank} = \frac{1}{m} \sum_{i=1}^m |Rank_{i,ref} - Rank_{i,SA}| \quad (4)$$

Potential improvements from production and consumption changes

We tested whether the current global nut portfolio could be optimized by shifting the current share of each nut in global production and consumption towards a pattern aligned with the baseline MCDA rank order. We evaluated the relative shift in environmental, nutritional and social impacts from current global nut production patterns against the potential impacts from production and consumption aligned with the baseline MCDA rank order. The current weighted global average of each indicator for current nut production and consumption was calculated from the quantities of nuts available in the food system from 2016 to 2018 as reported in FAOSTAT (Supplementary Fig. S2, Table S16) and the performance of each nut in the MCDA model. For comparison, we calculated an updated consumption share for each nut by dividing the MCDA baseline score of each nut by the sum of all nut scores. This updated share was used to calculate a new weighted global average. The weighted global average for each indicator was calculated from the share and performance of each nut variety. As Brazil nuts

are wild-harvested, we also tested a scenario with constant Brazil nut consumption.

Results

Rank order of alternatives

In the baseline scenario using correlation-based weights (CRITIC) and geometric aggregation, walnut ranked highest (Fig. 2, Table S13). Walnut had the top score on dietary context (measured by NQI) and scored greater than the average for all criteria except nutritional quantity (measured by NRF) and gender gap, where scores were near the average (Tables S11, S12). The second-ranked alternative, sunflower seed, performed well across all indicators, with the best performance in the NRF index, labor rights and gender gap, and better than average performance against all criteria aside from forced labor (Table S11). Brazil nut also had top performance for three criteria, but worse than average performance on nutritional and several social categories led to a lower overall ranking of 3 (Tables S11, S13). However, every nut had some degree of inconsistency across all indicators, so no dominance occurred before weighting and aggregation.

Despite poor performance on both nutritional indicators, chestnut ranked in the middle of the rank order (7) due to above-average performance on social and environmental dimensions. Cashew was ranked last by this model as the nut performed worst on GHG emissions, LSFP, child labor and working poverty, and below average on all other indicators aside from gender gap and work safety, where cashew performed slightly better than average and outperformed walnut. One contributing factor to cashew's poor environmental performance may be statistical, as cashews have the smallest nut to shell ratio (0.3) out of all other nuts and seeds considered. However, this factor would not influence social and nutritional dimensions.

Overall, the model prioritized consistent performance. Alternatives occupying the top three ranks also had the best average normalized scores across all criteria, and the normalized average score of cashew across all criteria was nearly half that of sesame, the alternative with the second smallest average value (Table S12). Alternatives with greater variance across indicator performance, such as pistachio, chestnut and almond, generally ranked in the middle or bottom third. No alternative with the worst performance on any indicator ranked higher than 6.

Sensitivity analysis: weighting and aggregation

Across six alternate weighting and two aggregation methods, the average change in rank for all alternate methods was about one rank position (Tables S13, S14). Such methodological choices primarily impacted rank change of middle-ranked alternatives, as the top- and bottom-ranked alternatives remained stable. Nuts with more consistent performance across all indicators, such as walnuts, sunflowers and cashews, were less impacted by weighting or aggregation changes than nuts with more inconsistent performance, such as chestnuts and almonds (Tables S13, S14).

Cashew rank order for all weighting methods did not change with the aggregation technique, indicating that overall performance on each criterion was sufficiently poor that compensation did not lead to a meaningful increase in rank (Fig. 3). Only for nutrition-focused weighting, the rank improved by one position using either aggregation method (Tables S13, S14).

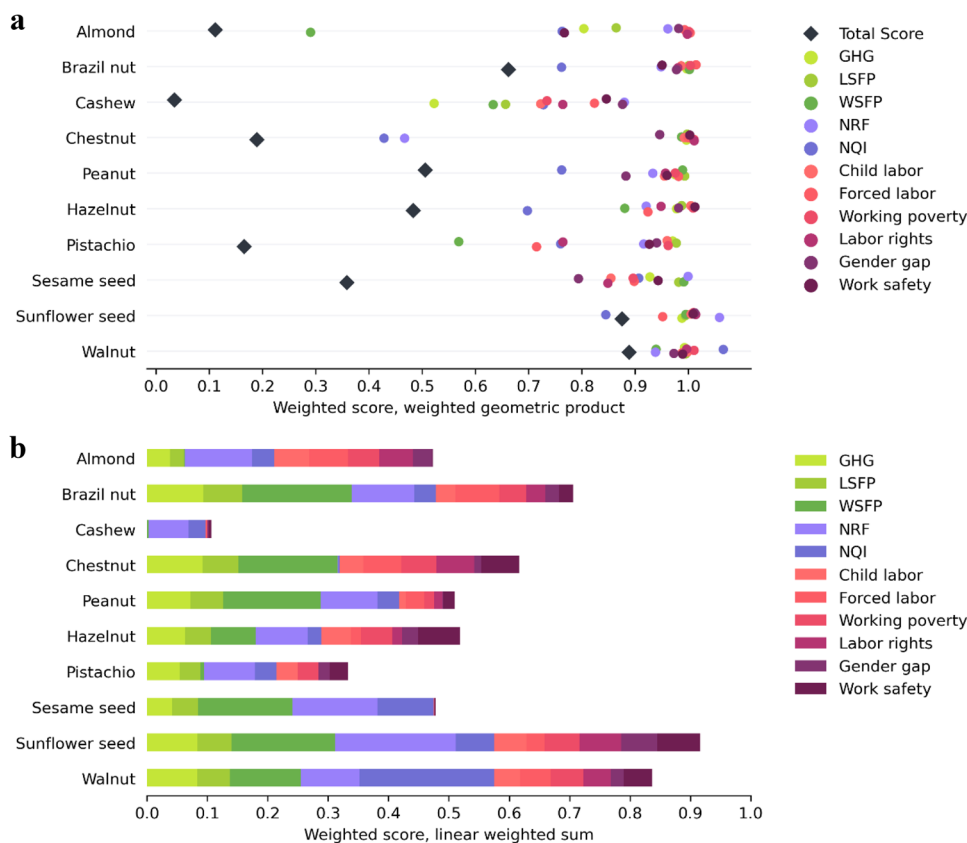
Chestnut underwent the largest rank change across alternate weighting and aggregation methods. Under linear aggregation, chestnut's low nutritional value could be compensated by the relatively good performance on social and environmental dimensions (Fig. 2) for a final rank of 4 (Table S14). However, in cases where nutritional criteria

were highly weighted, such as the entropy method or the nutrition or environment and nutrition weighting scenarios, chestnut's rank was reduced to 9 or 10 regardless of aggregation method (Fig. 3, Tables S13, S14).

Linear aggregation caused a rank reversal for the top-scoring walnut and sunflower seed for baseline and equal weighting scenarios (Tables S13, S14). Aside from these cases, the pattern of walnut and sunflower seed remained stable across aggregation methods, which is expected given the similar weighted scores of both nuts (Fig. 3). The wild-harvested Brazil nut increased to the top rank within the environmental weight scenario, the only instance another nut aside from sunflower and walnut was ranked 1 or 2.

The nutrition-focused weighting scenario was tied with social for the largest change in ranks (1.4) from baseline aggregation, driven by chestnut (7–10), sesame (6–3) and almond (9–6). Both seed varieties performed better than average on the nutritional dimension but scored below walnut due to walnut's high NQI performance. Walnut's advantage in the NQI scores is driven primarily by omega-3, derived from the relatively high content of ALA omega-3 fatty acids and low global adequate consumption of omega-3 fatty acids (globally consumed at 35% of recommended intake). Walnut's overall performance on NQI was nearly perfectly positively correlated with the total omega-3 score (0.97, $p < 0.001$) across all countries. However, sesame seed

Fig. 2 Total score and contribution of weighted criteria scores, baseline weights. **a** Weighted geometric product aggregation, **b** Linear weighted sum aggregation. Final aggregate scores range from 0 to 1. Values greater than 1 in **a** are due to the normalization of aggregate domain scores before the second weighting and aggregation step



has a more balanced nutritional profile than walnut, with high NQI scores for calcium, zinc, linoleic acid, iron, and ALA.

Overall, final aggregated scores were distributed relatively evenly across the 0–1 score interval (Fig. 3). CRITIC distributed weights fairly evenly across indicators (Table S10), which also led to a similar scoring pattern to equal weighting. The entropy weighting method was superior at stratifying alternatives into top, middle and low scores, but otherwise no natural clusters of alternatives could be identified (Fig. 3). Although rank reversal was observed for sunflower seed and walnut in environmental and social weighting scenarios, the absolute final scores were similar. For the weighting scenarios emphasizing a particular dimension, some rank changes occurred in middle-ranking alternatives with good performance on that dimension. For ranks per dimension (full weight applied to a single dimension), see Table S15.

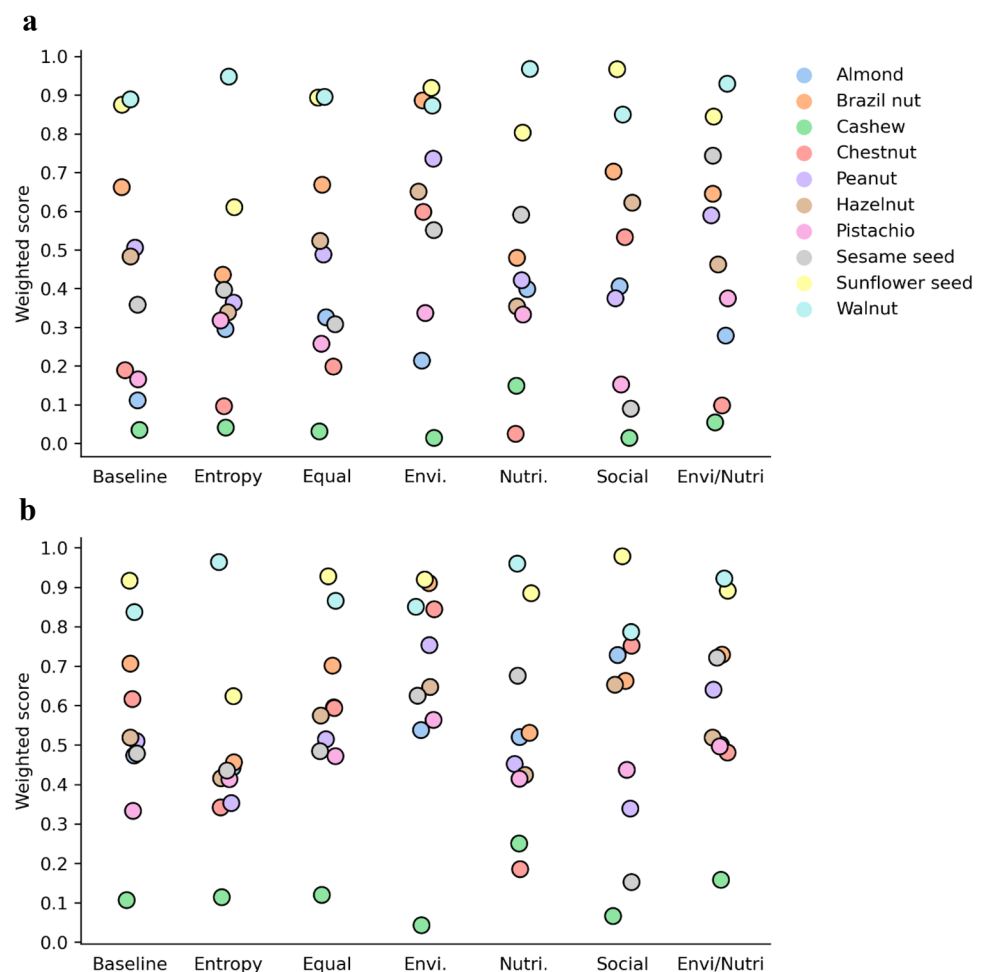
Sensitivity analysis: country-level values

We performed a sensitivity analysis using country-level data for nut production and consumption following two

sourcing contexts (sourcing country selection based on a probability distribution corresponding to global production volumes, and sourcing linked to consumption country if production is present; see SI Sect. 1.8.2. for further detail). Each run represented the rank order of nut production and consumption within a single country context using country-level values. This sensitivity analysis tested the variability of baseline ranks to variations in country-level input data given constant weights and geometric aggregation. Despite the apparent variations in country-level production impacts (Fig. S6), the rank order pattern for both analyses remained relatively similar to the baseline scenario (Fig. 4).

Sunflower seed and walnut both ranked in the top two positions. The top-ranked alternatives had slightly better outcomes in the analysis with sourcing selected independently from the consumption country. In this case, sunflower seed had a median and mode rank of 1, and the best average rank (1.7). When linking consumption and production, sunflower seed had a higher median rank than walnut, although both nuts had the same average rank (3.3).

Fig. 3 Scores of alternatives per weighting scenario, (a) weighted geometric product, (b) linear weighted sum



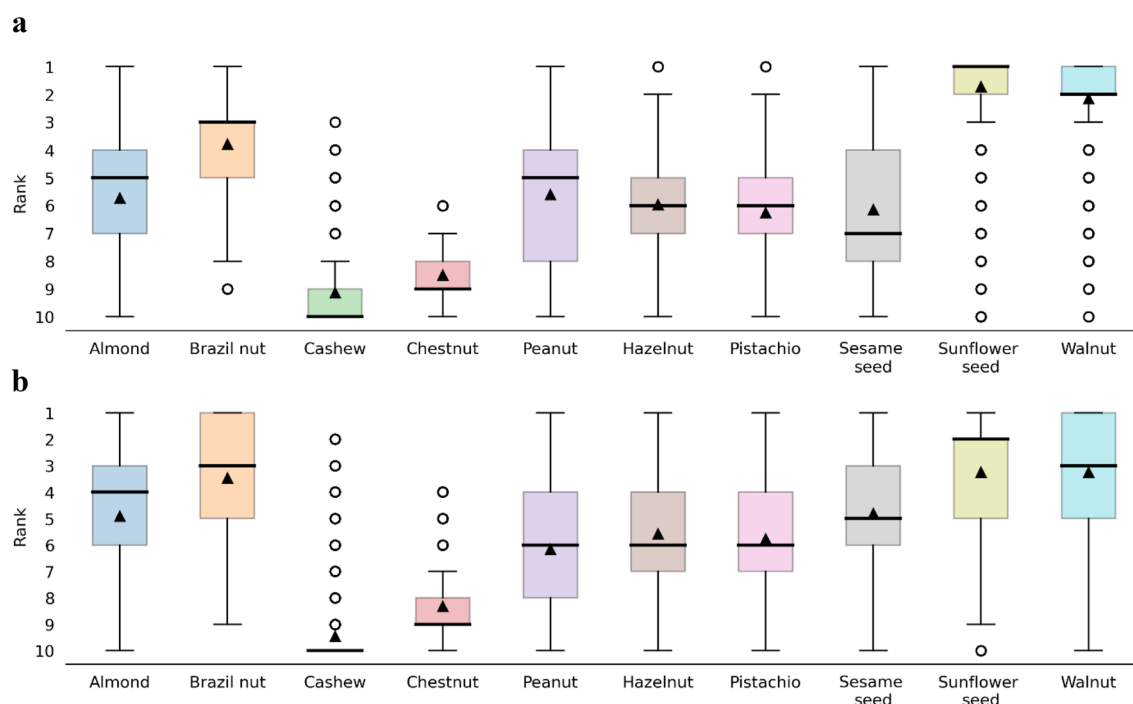


Fig. 4 Rank distribution from country-level analysis. **a** Sourcing country selected from global producers, **b** sourcing linked to consumption country. The triangle depicts the average

Cashew had the lowest median rank in both contexts, reflecting the baseline rank order. Although cashew's poor performance on a global scale can be partially attributed to the presence of extreme outliers for cashews for GHG emissions and the LSFP, the average performance on social and environmental criteria was worse than other nut types. For chestnut, the low ranking is again attributable to relatively low nutrient quantity by mass.

Within this sensitivity analysis, the average rank change for all nuts was 1.7 and 2.1—greater than the rank change from different weighting or aggregation methods. This suggests a greater model sensitivity to input data rather than weighting or aggregation method. Due to the nature of international trade of raw and processed nut products, it is unlikely that most countries would completely fill domestic demand with domestic production. Thus, the analysis with sourcing from a global pool of producers best simulates the global weighted averages, as the values were selected with probability based on total production volume.

Rank order clusters

Clusters of alternatives were formed from rank order in baseline and sensitivity scenarios (Fig. 5). Due to the even distribution of scores in the baseline ranking, alternatives were categorized in top (1–2) and bottom (9–10) clusters

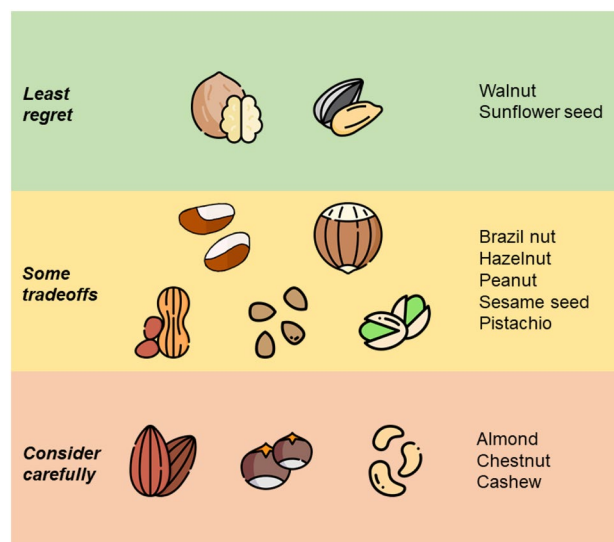


Fig. 5 Nuts grouped into top, middle and bottom rank clusters. Icons designed by Freepik from www.flaticon.com

based on baseline ranks and if ranked in these positions in at least three of the sensitivity analyses. The remaining nuts were assigned to the middle group. Although all alternatives aside from sunflower seeds and walnuts have some trade-offs from worse-than-average performance in at least one dimension, the bottom-ranked alternatives should be carefully

considered when selecting nut varieties for consumption or cultivation.

Impact from changing production and consumption patterns

With adjusted consumption patterns as described in “Sect. [Potential improvements from production and consumption changes](#)”, most global nut consumption performance improves across all impact categories relative to current consumption patterns, with an average absolute change of 23% across all impact categories (Fig. 6). The largest potential improvements in impact in the MCDA rank consumption scenario are for working poverty risk (50%) and GHG emissions (40%) (Table S17). Total impacts from adjusted nut consumption worsen only for forced labor (− 12%). Forced labor risk increase is associated with the relatively greater consumption of sunflower seeds, hazelnuts, and sesame seeds. However, the overall forced labor risk for this consumption pattern is still improved compared to the global unweighted average across all nuts (Tables S11, S17). Keeping Brazil nut consumption constant resulted in a slightly smaller average improvement (20%) across all impact categories (Table S18, Fig. S13).

Discussion

Results in the context of previous research

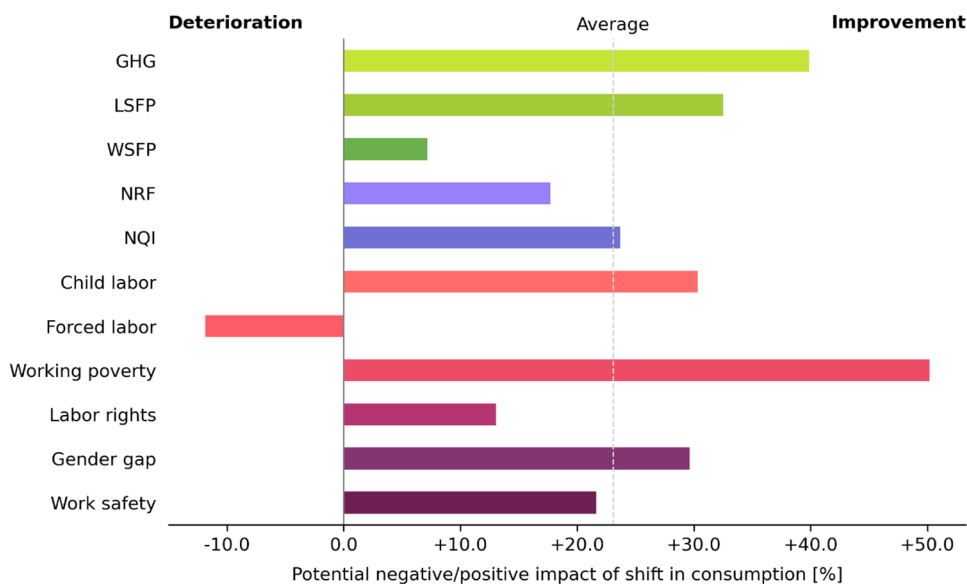
Sustainable diet studies assessing health and nutrition may not incorporate environmental aspects, and studies with an environmental impact may lack a quantitative vigor for nutritional aspects (Green et al. 2020). This study complements

the work of Masset et al. (2014) and Scherer et al. (2019) on the nutritional dimension by including a nutritional context indicator and extending the nutritional quantity index to essential amino acids and fatty acids. Our work also measures individual food products within a food group at both a global and country level, complementing studies addressing sustainable diets but with more general food groups or a single-country scope (Chen et al. 2019; Paris et al. 2021). We also build on the environmental assessment of individual products of Karlsson Potter and Rööös (2021) by providing additional nutritional and social context and country and global level results and illustrating the potential importance of including climate impacts from land use and land use change. Whereas all nuts are rated in the favorable green or green star category in that study, we find that the carbon footprint for some nuts would not fall within planetary boundary thresholds proposed if land use change impacts were included. Similar to our findings, Vanham et al. (2020) and Sokolow et al. (2019) both found almonds, cashews and pistachios to be relatively worse-performing and groundnuts more advantageous, although a smaller set of indicators was used for those assessments. In contrast, Karlsson Potter and Rööös (2021) evaluated conventional tree nuts in the worst performance threshold, while organic nuts, especially chestnuts, were evaluated as more sustainable choices.

Reflection on the MCDA approach and indicator measurement

Our model demonstrates the viability of statistical weighting and aggregation to produce a single score from numerous sustainability criteria. Generally, multi-indicator assessments of food systems present results aggregated only within a dimension, usually through simple averages.

Fig. 6 Potential effects from a shift in consumption aligning current patterns with MCDA rank order. Improvement represents a net benefit, and deterioration represents a net detriment to global performance



While individual indicator performance is best for identifying hotspots, a single score better facilitates decision-making across a set of alternatives. Here the combination of statistical weighting and partially non-compensatory aggregation penalizes alternatives that would otherwise score moderately using equal weights and linear aggregation (e.g., almond, chestnut) despite poor performance on at least one indicator, which better reflects a ‘strong’ sustainability perspective. The statistical weighting scenarios used here are useful for a general audience, as CRITIC and entropy perform similarly to equal weighting but reduce double-counting. However, global stakeholder input on the objective hierarchy construction and criteria weights would strengthen the recommendations. After mapping relevant stakeholders (Reed et al. 2009), stakeholder input to define the objectives and elicit weights can be obtained through interviews, workshops or online surveys (Marttunen et al. 2015). Further development of a single score can be enabled by measuring endpoint indicators such as human health or ecosystem functioning.

Although MCDA facilitates a more comprehensive assessment of food systems, bias can arise from the objective hierarchy construction and indicator selection (Marttunen et al. 2018). The 11 indicators chosen here aim to reflect the multifaceted dimensions of sustainability proposed by the UN SDGs and the FAO. Criteria unquantifiable at our chosen crop and country scale, such as food security, food accessibility, and cultural heritage, were excluded due to a lack of publicly available data sources. Economic indicators addressing consumer and producer objectives merit further exploration in an extension of this framework. The EAT-Lancet diet of Willett et al. (2019) has been criticized based on affordability, and nuts and legumes are the second-largest expense within that diet (Hirvonen et al. 2019). However, farm gate price or economic value distribution throughout the supply chain should be investigated along with retail prices so that low consumer prices are not prioritized at the expense of producer incomes, working conditions, or environmental health. Half of the world’s nuts are produced for export (Poore and Nemecek 2018), so future research addressing nuts and other cash crops should consider the incentives associated with the continued production of these crops. Especially if a similar framework were to be applied on a local level, the economic value of local production could provide relevant information about trade-offs for political decision-making. The intersection of the rates of working poverty in nut supply chains compared to economic value generation is recommended for inclusion in any further research. Recent efforts by the FAO to include more socio-economic indicators in FAOSTAT is an encouraging development, although data gaps are still present.

Reflection on social impact assessment

We proposed a high-level social risk assessment methodology that uses publicly available secondary data to estimate the probability of adverse social impacts of a crop based on global sourcing. The social risk assessment method proposed can serve as a first step to identify potential risk hotspots linked to agricultural supply chains. Although less detailed than S-LCA data available as part of a private database, such as the Social Hotspots Database (NewEarth B 2021) or PSILCA (GreenDelta 2021), this approach is transparently documented for any individuals interested in applying the method or using this data for further research. Additionally, the use of a globally relevant indicator framework may be beneficial for highlighting impact categories that local stakeholders overlook (Mattila et al. 2018). Overall, as recommended by Janker and Mann (2020), a more standardized approach to assessing social sustainability within the food system would be beneficial for future research assessing social impacts, as the lack of similar studies for comparison limits knowledge exchange and systematic improvement of social impact assessment methods.

Some limitations of this method can be addressed with future research efforts. Our social risk assessment method is limited to nut production at the farm level. If all nuts were also processed in their production country, the relative risk would be equivalent. Given global nut trade patterns, this may be too coarse of an assessment. Linking social risk to country of origin without distinguishing between specific crop production practices eliminates some nuance between production and harvest practices, such as greater exposure to harmful chemicals used more frequently in one crop than another or different risks present in manual labor or machinery operation. For instance, cashew processing can be labor-intensive and hazardous due to the risk of injury from cutting or from skin damage from the acidic cashew shell nut liquid (Dendena and Corsi 2014), but different social risks can be present if harvest is mostly mechanized (e.g., peanuts) or by hand (e.g., Brazil nuts). Examining pesticide and machinery inputs for a specific nut using LCA inventory data and extrapolating the relative risks based on the degree of mechanization or degree of pesticide use, informed by S-LCA impact pathways (United Nations Environment Programme 2020, p. 95), could improve this method. Additionally, expanding the social impact model to include positive social impacts such as economic value added or investment may be explored with tools such as multi-regional input–output analysis (IOA). Processing and labor inputs, as well as impacts specific to certain countries, could also be better addressed with an IOA model. Several models using IOA to assess embedded social risk and impacts exist; see Hardadi

and Pizzol (2017); Mattila et al. (2018); Simas et al. (2014); Weidema (2018); Xiao et al. (2017).

Policy relevance and further applications

The nut and seed rank order resulting from this MCDA is not definitive; results should spark further research and policy discussions about the potential benefits and trade-offs of increased consumption of nuts for healthy and sustainable diets rather than serve as a blueprint for production and consumption. Our model can be suitable for a more detailed country-level assessment, as all data aside from nutrient quantity were collected on a country level. For instance, the input values can be tailored to the specific production or import mix of a country or region for greater relevance to that specific context. The hypothetical impact assessment from shifting consumption patterns highlights potential benefits of modifying nut consumption patterns to align with better-performing varieties. However, this scenario would also require extensive changes to production and consumption patterns, such as more than a 1300% increase in sunflower seed consumption.

All potential impacts described in this study represent a possible relative change given the extension of current conditions, as the changes to environmental, nutritional and social performance are linked to present production and consumption patterns. Attributional LCA approaches assume linear scaling and marginal changes to background systems (Guinée et al. 2002). The limitations for recommending policy action based on an attributional LCA are well known; see Plevin et al. (2014) for a full discussion. Future relative and absolute impacts are likely to shift with an expansion of nut consumption or dietary transitions, but static models, such as the one used in this study, reflect conditions where all other things remain equal. Still, the consumption scenario indicates that—hypothetically—nut production and consumption could be ‘optimized’ with only one trade-off (forced labor), which shows that it may be worthwhile to pursue future investigations on how to scale up some kinds of nuts.

Two possible interpretations following this model’s results are that dietary recommendations should discourage nuts with poor overall performance, or that industries and consumers should choose nuts sourced from countries associated with better environmental or social performance. However, these actions may not always be feasible or desirable in practice. The context surrounding cashew, walnut and sunflower seed production illustrates the complexities of assessing food cultivation systems holistically.

Cashews are economically important to smallholder farmers and certain economies. For instance, the economic impact of cashew production is particularly notable within Guinea-Bissau, where cashews provide 25 to 35% of annual household income (Hanush 2016). Households dependent on

cashew profits to purchase or trade for staple crops like rice are vulnerable to food security issues during global market price fluctuations (Catarino et al. 2015). Reducing consumption may exacerbate the same conditions that led to cashew’s poor sustainability performance and can undermine some of the environmental benefits such as erosion prevention. Strategies to improve the environmental impact of the West African cashew sector include introducing intercropping of staple crops within orchards, introducing high-yielding varieties to improve productivity, and better using cashew byproducts such as cashew apples (Monteiro et al. 2017). Social risks may be mitigated through greater supply chain transparency and investment in improving worker and community livelihoods. Still, closer monitoring is necessary to ensure that economic gains from increased export value create meaningful social impacts for farmers and communities.

Even with walnut’s high performance on the three dimensions of sustainability, weak spots are possible. The gender gap is one vulnerability, which can intersect with performance on other dimensions. In Iran, the third-largest walnut producer, female farmers were found to have lower adaptive capacity to climate change compared to male farmers due to lack of access to resources and asset ownership (Jamshidi et al. 2020). Walnut production has expanded steadily in China, the largest producer, but small walnut farms lack bargaining power for price negotiations, struggle with price competition from plantations started during reforestation initiatives, and lack the financial resources to invest in value-adding activities such as shelling and processing (Yan et al. 2017; Zinda and He 2020).

Future dietary recommendations may benefit from explicitly encouraging seed consumption. Seeds performed well on nutritional criteria, outperforming all culinary nuts except walnut. Sunflower seeds performed particularly well across all dimensions, although annual crops, such as sunflowers, less effectively sequester soil carbon than perennial crops (Kroodsmas and Field 2006). Sunflower seeds are produced in the second-largest quantities after peanuts, but only a fraction of sunflower seeds are consumed as seeds in the global food supply, even after accounting for oil production for human consumption (Fig. S5, Table S16).

For sunflower seeds, the sizable gap between current consumption and total production due to use in non-food applications such as biofuel production or animal feed suggests limited crop expansion would be needed to meet increased consumption patterns, assuming seed use patterns could be adjusted. Replacing some level of peanut consumption with sunflower seeds, especially in regions where sunflowers are cultivated and peanuts are imported, such as Europe, may improve overall sustainability outcomes for nut consumption. While sunflower seed and its resulting oils and residual materials are a versatile product for many agricultural and industrial uses, reducing sunflower seed use in industrial

applications may be beneficial. Sunflower-derived biodiesel under current production practices does not represent a sufficient environmental improvement from conventional diesel (Spugnoli et al. 2012), and LCA results are mixed for the overall environmental advantage of sunflower-based biofuels over other oil crops (Fazio and Monti 2011; Iriarte et al. 2010). In animal feed, sunflower seeds and sunflower seed meal are judged to be an adequate replacement for soybean meal for pigs (Rodriguez et al. 2013) but less suitable for poultry (Leinonen et al. 2013), which indicates that the feed may be used for convenience or economic reasons rather than particular nutritional attributes.

Every nut and seed supply chain has more context to consider than final ranking, so no nut should be considered a lose-lose-lose choice across all dimensions. Rather, our research suggests that there is potential for overall positive effects from shifting to more sustainable varieties and highlights where additional attention from producers and consumers is necessary to address adverse impacts. Additional detailed analysis of the socio-economic and environmental trade-offs from scaling up production, similar to the work of Stratton et al. (2021) on fruit and vegetables, would be useful for understanding practical pathways to sustainable nut consumption. The hotspots and weaker performance areas identified here can direct future research efforts on the role of nuts in sustainable diets.

Conclusions

We developed a multi-criteria analysis method using statistical weighting techniques and partially non-compensatory aggregation to evaluate nuts and seeds across 11 environmental, nutritional and social indicators, including a proof of concept for a social risk assessment approach. Although frequently considered as a homogenous food group, our model identified three performance classifications: walnut and sunflower seed in the top rank positions; Brazil nut, hazelnut, peanut, sesame seed and pistachio in middle-ranked positions; and cashew, chestnut, and almond in the bottom ranks. Barring bias in indicator selection, the stable outcomes across sensitivity analyses on weighting scenarios, aggregation methods, and country input data suggest a robust result.

A shift in consumption patterns aligning with the outcome of this decision model would potentially improve environmental, nutritional and social performance of total nut consumption on all indicators by an average of 23%, but forced labor performance would worsen. The socio-economic impacts of the production of a specific crop are challenging to fully address in a decision model, and economic aspects should be addressed in future research. While a relative increase in walnut and sunflower consumption

may have positive benefits, smallholder inclusion and local impacts should be studied further to avoid adverse effects. The bottom-ranked cashew's potential importance to local economies despite the nut's below-average sustainability performance illustrates the challenge of translating rank order into comprehensive policy measures.

The results from this study should not be interpreted as a definitive suggestion for consumption patterns but rather as an exploration of how to improve the sustainability performance of nut and seed consumption. The excellent performance of sunflower seed across all impact categories makes a strong case for broadening the scope of how 'nut' consumption intakes can be met. The MCDA results highlight potential hotspots, and the insight into trade-offs and synergies between sustainability dimensions can inform policy around sustainable food systems or dietary guidance. Future research can explore the feasibility of scaling up each type of nut to reach global consumption targets and developing a model to optimize production and consumption patterns given the complexities within each nut production system. Stakeholder input should also be an indispensable input for future analysis given the interrelation of environmental, nutritional and social dimensions. Overall, this research provides a first step towards creating a decision analysis tool to compare alternatives within a food group across three sustainability dimensions, which is applicable well beyond the case of nuts.

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