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To cite this article: Ramin Ghamkhar and Andrea Hicks 2021 *Environ. Res.: Infrastruct. Sustain.* **1** 021002

ENVIRONMENTAL RESEARCH
INFRASTRUCTURE AND SUSTAINABILITY

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OPEN ACCESS

RECEIVED
19 April 2021

REVISED
2 June 2021

ACCEPTED FOR PUBLICATION
29 June 2021

PUBLISHED
27 July 2021

LETTER

Spatially explicit life cycle assessment of fish: comparison of local vs imported provision in Wisconsin

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Keywords: life cycle assessment, spatially explicit analysis, seafood, sustainability, food transportation

Supplementary material for this article is available online

Abstract

The global fish supply chain handles ∼179 million tons of product annually (as in 2018). Transportation and distribution are an important part of fish supply chain, as fish and shellfish are one of the largest globally traded food commodities with a trading value of ∼$153 billion in 2017. Here we show that disregarding the environmental impacts of fish transportation, either land transit or flight, neglects a noteworthy portion of total fish provisioning environmental impacts. We identified that local fish provision, considering (1) all Wisconsin counties as production points, (2) cities of Chicago, Milwaukee, and Minneapolis as consumption points, and (3) effective, semi-effective, and ineffective space heating approaches, has significantly lower environmental impacts than imported fish provision, considering flight transportation from offshore production points. Meaning the necessity to elevate local fish production capacity to enhance the environmental sustainability of fish provision is essential, despite potential elevated heating demands for cold-weather aquaculture.

Abbreviations

Acronym	Full phrase
RAS	Recirculating aquaculture system
IMTA	Integrated multi-trophic aquaculture
LCA	Life cycle assessment
km	kilometer
Q	Thermal energy
M	Mass
C	Specific heat
T	Temperature
ρ	Density
V	Occupied space
SC	Scenario
m	meter
km	kilometer
kg	kilogram
a	per annum
kJ	kilo Joule
SI	Supplementary information
WI	Wisconsin
IL	Illinois
MN	Minneapolis
USLCI	United States Life Cycle Inventory

EPA	Environmental Protection Agency
TRACI	Tool for the reduction and assessment of chemical and other environmental impacts
ODP	Ozone depletion potentials
GWP	Global warming potential
PSP	Photochemical smog potential
ACP	Acidification potential
EUP	Eutrophication potential
HHCP	Human health carcinogenics potential
HHNCP	Human health non carcinogenics potential
REP	Respiratory effects potential
ECP	Ecotoxicity potential
FFP	Fossil fuel depletion potential

1. Introduction

Since 1961, the average annual increase in the world's fish consumption has outpaced population growth. Annual per capita fish consumption has increased from 9.0 kg in 1961 to 20.2 kg in 2018, which represents a 124% increase of annual per capita fish food consumption worldwide [1]. Concerns regarding the environmental sustainability of the supply chains, including fish, have also increased in conjunction with the growing consumption [2–5].

In order to quantitatively evaluate the environmental sustainability of fish consumption, life cycle assessment (LCA) could be utilized throughout the supply chain (fish production, distribution and aggregation, food processing, marketing, purchasing, preparation and consumption, and waste management and recovery) [6]. However, due to the complexities in the whole chain evaluation, the majority of previous studies have taken the cradle-to-gate approach, in which only the environmental impacts of fish production stage is assessed [7–10]. In production scenarios that a recirculation system is utilized (e.g. recirculating aquaculture systems (RAS), aquaponics, integrated multi-trophic aquaculture (IMTA)), many studies have addressed energy requirements as the major contributor of the environmental impacts [2, 3, 11–16]. Contrarily, in production scenarios where a non-recirculation system is utilized (e.g. flow-through, net pen) feed ingredient production is identified as the main contributor of environmental impacts [17–21].

Previous LCA studies have been predominantly focused on either (a) protecting aquatic species (targeted or non-targeted) [22–27] or (b) reducing the environmental impacts [27–31] in the production stage. As a result, only a minimal number of studies have quantified the environmental impacts associated with transportation in the evaluations [32–34]. Additionally, some studies have suggested that transportation distance contributes a small portion of overall environmental impacts of food systems [35, 36]. However, as concluded in some other studies, transportation has the potential to contribute greatly to the overall environmental impacts of food supply chains (due to potential considerable energy consumption and travel distance), including fish production, and considering a cradle-to-market approach [1, 37–40]. For example, Bell and Horvath [41] estimated the cradle-to-market greenhouse gas emissions of US fresh produce (oranges as a case study), considering production, processing (post-harvest), packaging, and transportation, to assess the relative importance of transportation and seasonality in total carbon footprint. Their results indicated that transportation impacts could contribute to 4%–54% to the overall life-cycle impacts depending on transportation mode and distance (corresponding to Californian oranges delivered to Los Angeles by rail, and Texas oranges delivered to New York city by truck, respectively).

The prospective increasing demand for fish provision is shifting the dialogue as to whether it is more environmentally preferable to produce local, with potential elevated heating demands in a cold-weather (e.g. Wisconsin), or import, with potential elevated transportation demands [20].

Here we perform a holistic analysis of the environmental impacts associated with fish food production and transportation offsets with a case study of Wisconsin (Midwest US) as a cold-weather location, undertaking a spatially-explicit approach. First (phase 1), we evaluate the elevated heating demands associated with local indoor aquaculture at a county-level, using varying space heating scenarios. Second (phase 2), we evaluate the transportation demand differences, in terms of mode and distance, among local and imported production, considering scenarios of consumption in most populated cities near Wisconsin (i.e. Chicago, Milwaukee, and Minneapolis). Third (phase 3), we perform a comparative analysis of the environmental impact trade-offs, analyzing local and imported fish provision alternatives using varying consumption and production scenarios (figure 1).

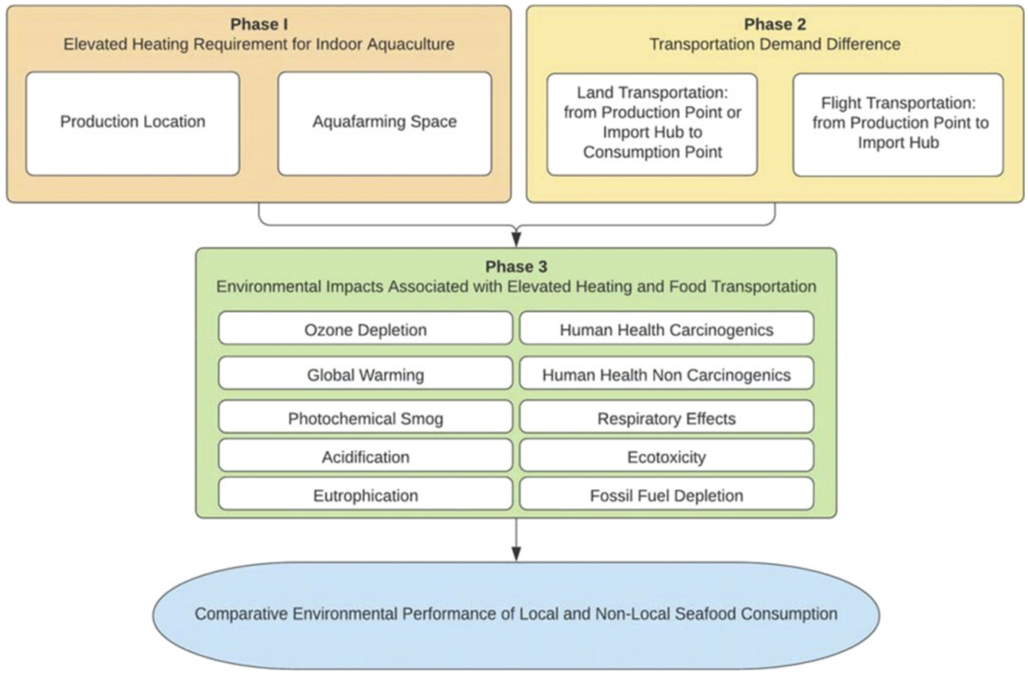

Figure 1. Framework chart for the comparative environmental performance evaluation of local vs imported fish production.

2. Methods

Comparative life cycle assessment (LCA) is used as the methodology to evaluate the comparative environmental impacts of fish provision scenarios [42]. The specific LCA configurations are described below and expanded upon in the supplementary information (https://stacks.iop.org/ERIS/1/021002/mmedia) [43].

2.1. Scope and system boundary

The main goal of this study is to determine the environmental impact trade-offs between local vs imported fish provision, incorporating the impact of transportation. For this purpose, the elevated heating demands due to space heating requirement for local fish production, considering all counties in Wisconsin as production points, are evaluated using three realistic alternatives. Transportation requirements are also estimated using (1) flight transportation with refrigeration for off-shore transport (2) land transportation with refrigeration for on-shore transport, using (1) all Wisconsin counties as local fish production points and (2) Chicago, Milwaukee, and Minneapolis as consumption points. We are not including the other processes contributing to the environmental impact of the fish production, such as fish feed.

2.2. Evaluation criteria

SimaPro 8.2.0 is used as the modeling platform to quantify the environmental impacts, using databases from EcoInvent3 [44] and USLCI [45]. The tool for the reduction and assessment of chemical and other environmental impacts (TRACI) 2.1 (developed by US EPA) is selected for the characterization of environmental impacts. The impact categories evaluated in this study (abbreviation, unit) are ozone depletion potential (ODP, kg CFC-11 eq), global warming potential (GWP, kg CO_2 eq), photochemical smog potential (PSP, kg O_3 eq), acidification potential (ACP, kg SO_2 eq), eutrophication potential (EUP, kg N eq), human health carcinogenics potential (HHCP, CTUh), human health non carcinogenics potential (HHNCP, CTUh), respiratory effects potential (REP, kg PM2.5 eq), ecotoxicity potential (ECP, CTUe), and fossil fuel depletion potential (FFP, MJ surplus). Quantifying the environmental impacts using multiple impact categories provides the opportunity to have a comprehensive assessment and to analyze potential trade-offs in a holistic manner. For the purpose of this analysis, results are demonstrated using GWP as the pivotal impact category within the main text. However, quantified impacts with respect to other impact categories are also provided as supplementary information (SI) to highlight similar comparative outcomes with respect to other environmental indicators.

2.3. Functional unit

The functional unit for the quantification of elevated environmental impacts is unit mass (1 ton) of fish provision. For example, to quantify the elevated global warming potential (GWP) for local fish production, considering (1) effective space heating, (2) production point in Dane county, WI, and (3) consumption point at Chicago, IL, total CO_2-eq emissions were calculated for elevated heating demands and land transportation per ton of fish provided (32 kg CO_2-eq).

2.4. Heating demand estimation

Following the principles of energy transformation through thermal energy ($Q = MC\Delta T$), the overall thermal energy gained (or lost) for an indoor space is estimated as a function of temperature difference (indoor vs outdoor) and overall occupied space (ρV) [46]. Higher year-round heating degree days (HDD) for a location, corresponds to higher overall temperature difference (ΔT) for the indoor aquaculture system for annual production [47]. Therefore, counties with colder weather pose higher heating demands at fixed space heating configurations. Additionally, larger volume (V) of space occupied for indoor aquaculture results in larger mass (M) and elevated space heating demands, and vice versa. In addition, the heat loss is a function of how well insulated the indoor space is. To mimic real-case scenarios, a 'well insulated' space (corresponding to an enclosed space, in which walls are erected but not insulated and doors and windows covered with plastic sheeting or tarps) is assumed [48]. Overall occupied space per unit of annual fish production (m^3 kg^{-1} a) is estimated based on three realistic scenarios, representing ineffective [2] (SC1, 0.5 m^3 kg^{-1} a), semi-effective [49] (SC2, 0.05 m^3 kg^{-1} a), and effective [50] (SC3, 0.01 m^3 kg^{-1}). Aquaculture systems' overall occupied space could depend on a varying set of operational factors, including the systems' intensity level, available space, and rearing species. Although there is a lack of literature data on quantifying the systems' total occupied space in most aquaculture studies, the presented scenarios are providing a potential acceptable broad range with respect to required space per unit of production per annum, as they incorporate available data from cold-weather located research-scale and large size production systems. Natural gas (combusted at US industrial equipment) is used as the heating source. A conversion of 37 631 kJ to 1 m^3 natural gas is performed [51].

2.5. Transportation demand estimation

To estimate the required flight transportation for imported fish provision, the average mass-based distance from production point to Chicago port (as the closest designated port for perishable products) is estimated using contribution percentage of total tilapia imported to the US from different countries. Also, transportation distances from China (as the major contributor of US tilapia import) and Mexico (as the nearest significant off-shore production origin) were considered for final impact assessment to incorporate the range of ultimate flight transportation impacts. The commute distances (flight and route distances) are estimated using an online distance calculator [52]. Land transportation has been elicited using production points (Wisconsin counties) as starting points and consumption points (Chicago, Milwaukee, and Minneapolis) as destinations.

3. Results

We assessed and compared the environmental impact trade-offs for local vs imported fish provision, considering (1) local production points in all 72 counties of Wisconsin, (2) three practical space heating scenarios (ineffective, semi-effective, and effective), and (3) three consumption points at the three closest high population urban areas relative to Wisconsin (i.e. Chicago, IL; Milwaukee, WI; and Minneapolis, MN). For imported fish provision, we considered an average required travel distance based on average mass-based tilapia import data, in addition to travel distances from China and Mexico [53], using flight transportation with refrigeration unit as the preferred transportation mode [54].

3.1. Phase 1

Due to the relatively low year-round temperature in Wisconsin (Midwest US) compared to other widely known locations for practicing aquaculture, most of the fish production systems are located indoors. The overall occupied spaces for indoor aquaculture have a more significant effect on the production system's heating demand [2]. Assuming only an effective heating scenario, in which the total space is optimized and the system is well insulated, will ignore the empirical heating approaches that are currently undertaken for aquafarming [2, 55]. Hence, the heating demands corresponding to ineffective (scenario 1), semi-effective (scenario 2) and effective (scenario 3) space heating are evaluated using a spatially explicit approach (figure 2).

Figure 2 illustrates that shifting from one scenario to the other regarding total space heating (i.e. scenario 1 vs scenario 2 vs scenario 3) results in the change in heating demand by $\sim$1 order of magnitude (2599–3431 kJ kg^{-1} a for scenario 1, 240–318 kJ kg^{-1} a for scenario 2, and 48–64 kJ kg^{-1} a for scenario 3). Whereas, the relative significance of production location impact on heating demand is lower within the state (i.e. higher demands in colder locations, but at the same order of magnitude). This indicates that implementation of effective space heating strategies is of prime importance for practical improvement of systems energy saving and reducing the overall production environmental impact.

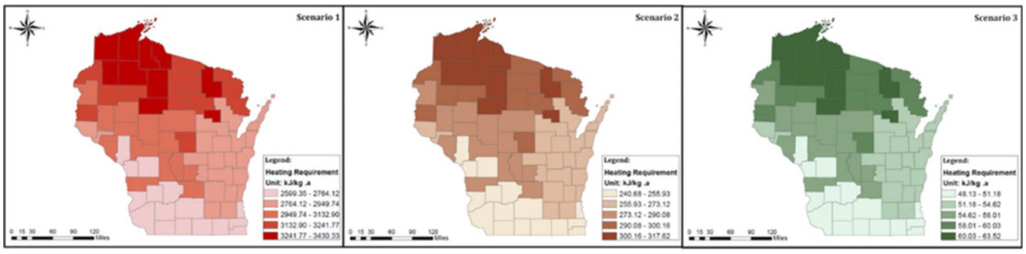

Figure 2. Estimated county-level heating requirements for indoor aquaculture. Scenarios represent different annual production capacities in terms of occupied indoor space (overall effective indoor building space per kilogram of live-weight fish produced per year); scenarios 1, 2, and 3 correspond to the production capacities of 0.54 m^3 kg^{-1} a (ineffective), 0.05 m^3 kg^{-1} a (semi-effective), and 0.01 m^3 kg^{-1} a (effective), respectively.

3.2. Phase 2

Land transportation using a truck with refrigeration is the main approach for fish in-shore transportation [56, 57]. To quantify the distance from fish production points (i.e. counties) or import hub (i.e. Chicago as the closest designated port for perishable items) to consumption points (i.e. nearest populated cities), the driving routes (in km) between all counties and consumption points have been elicited and tabulated (table S4 of the SI). Furthermore, due to (1) the majority of imported fish to the US being imported from East Asia (e.g. China, Taiwan, Indonesia), and (2) the importance of swift shipment for fish as a perishable item, flight transportation with reefer is the major approach for fish imports from overseas [54, 58]. We estimate the average distance from fish production point to the nearest import hub (Chicago port) as 10 550 km. To illustrate the prospective range of total flight transportation impacts due to high variability in distance from producers, flight transportation from (1) China (Mainland) with the distance of 11 310 km and (2) Mexico with the distance of 2469 km were incorporated as well.

3.3. Phase 3

We found a significant elevation of environmental impacts for imported fish provision compared to local fish provision due to remarkable environmental impacts associated with flight transportation with reefer (figure 3, tables S7–S13 of the SI). The environmental impacts of flight transportation (for imported fish) is at least ∼2 orders of magnitude higher than total elevated impacts of local fish provision (figure 3) based on average mass-based travel distance, and at least ∼1 order of magnitude higher based on import from Mexico (with lowest flight transportation environmental impacts) (figure 3).

Delving into the contributing parameters to the overall environmental impacts, we observe that >99% of flight transportation impacts, evaluating GWP and 9 other indicators, are associated to transport rather than operation (table S7 of the SI). The elevated environmental impacts associated with imported fish provision is mainly due to the remarkable distance, and optimization of operational strategies (e.g. refrigeration) is not tangibly mitigating the total environmental impacts.

For local fish provision, the major contributor to the elevated impacts significantly depends on (1) undertaken heating scenario and (2) ultimate consumption point. For instance, considering the implementation of effective space heating for local fish provision, land transportation contributes to >81% of elevated GWP, considering all Wisconsin counties as production points and the ultimate consumption in Chicago. However, the contribution of land transportation reduces down to 54%, considering ultimate consumption in Minneapolis and Milwaukee, which have shorter average distance to the production points (neglecting concurrent production and consumption in Milwaukee). Using semi-effective and ineffective space heating, we observed similar trends but with lower contribution of land transportation to the elevated environmental impacts (as low as 2%).

Despite the significant contribution of both land transportation and elevated heating demand to the local fish provision environmental impacts, shifting from one heating scenario to the other results in more steep changes in the overall impact contribution of land transportation (e.g. figure 4) compared to consumption points alterations, highlighting the significance of implementing effective space heating for local fish provision. Furthermore, in contrast with most previous studies, results showcase that the relative elevated environmental impacts of land transportation is beyond to be neglected in most scenarios. Heating is identified as a major environmental impact contributor in indoor aquaculture systems, particularly in cold-weather locations [59, 60]. For example, Ghamkhar, Hartleb [2] showed that heat has the greatest contribution environmental impacts compared to other parameters with respect to the GWP, ACP, HCP, REP, ECP, and FFP impact categories (i.e. 6 out of 10 TRACI indicators) in a cold-weather aquaponic system (located in Wisconsin). Land transportation has the potential to be significant in the case of fish distribution [32–34].

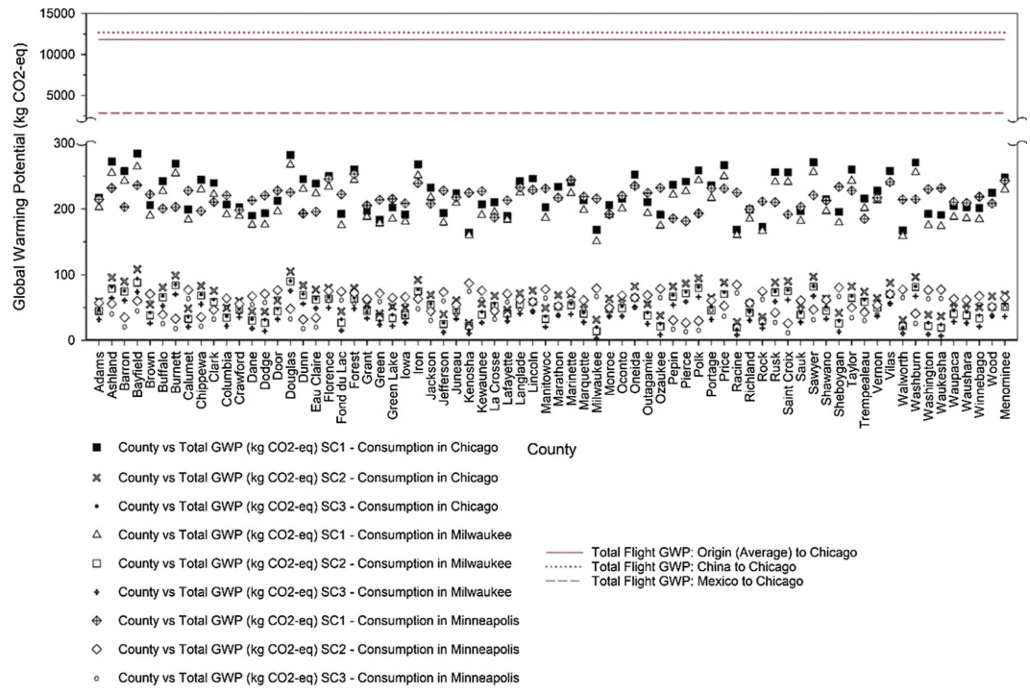

Figure 3. County-level quantification of GWP per ton of fish associated with elevated heating and food transportation using three space heating scenarios [SC1, SC2, and SC3; corresponding to scenario 1 (ineffective), scenario 2 (semi-effective) and scenario 3 (effective)] and three ultimate consumption alternatives (consumption in Chicago, Milwaukee, and Minneapolis).

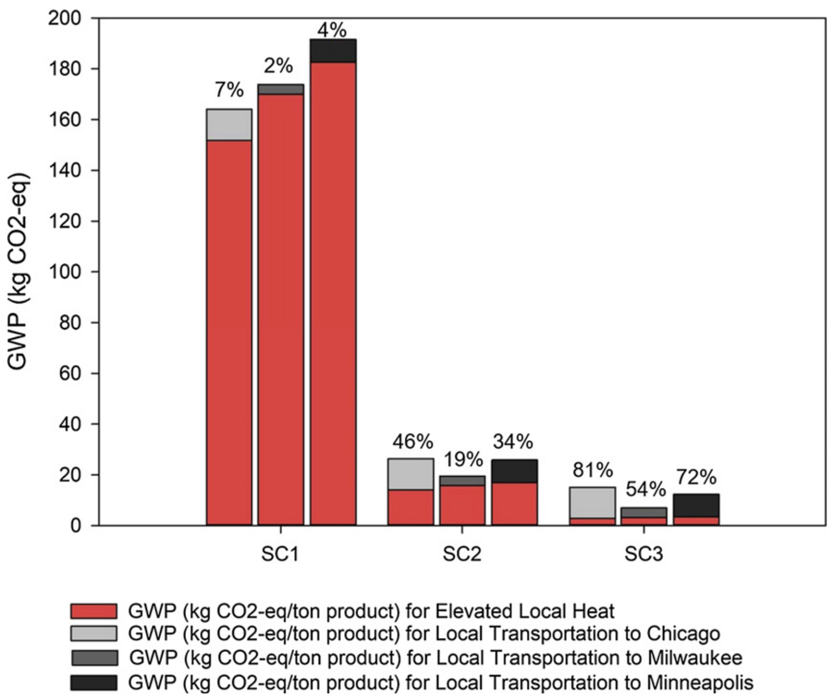

Figure 4. Elevated GWP from land transportation and heating demand. Represented data corresponds to the county point with lowest (minimum) land transportation contribution to overall elevated GWP. Percentages on top of the bars display minimum land transportation contribution to overall elevated GWP (%). SC1, SC2, and SC3 correspond to heating scenario 1 (ineffective), scenario 2 (semi-effective) and scenario 3 (effective), respectively.

4. Discussion

To illustrate the extent of relative environmental performance of local vs imported fish provision, we quantified the distance that a locally produced fish can be transported, using land transportation, to balance out the higher environmental impacts associated with imported fish provision, using GWP as the pivotal impact category and

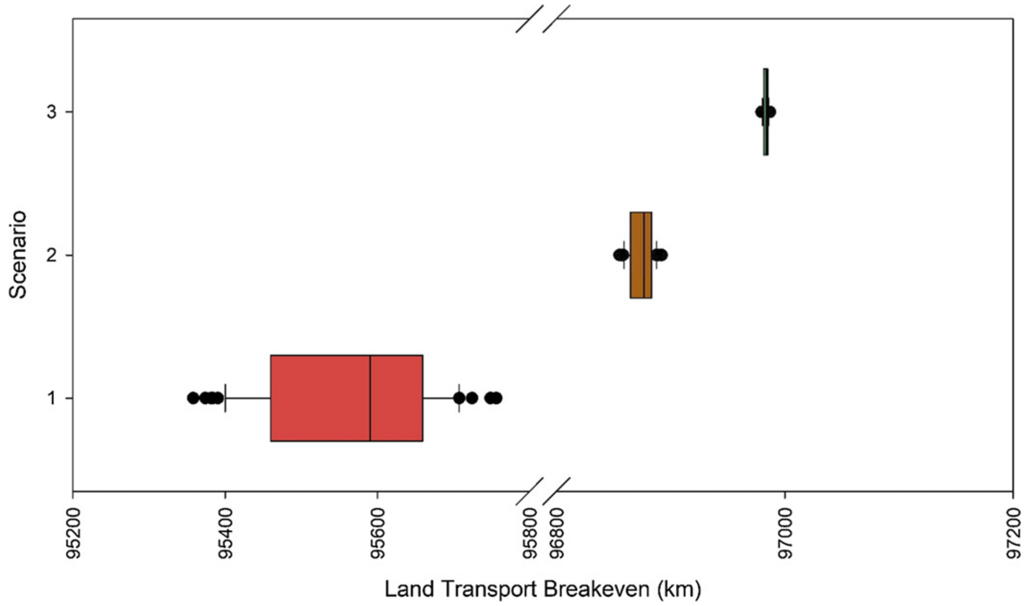

Figure 5. Breakeven analysis of land transportation for local vs imported fish provision using global warming potential (GWP) indicator. Scenarios 1, 2, and 3 correspond to heating scenario 1 (ineffective), scenario 2 (semi-effective) and scenario 3 (effective), respectively.

three elevated space heating scenarios for local provision [20] (figure 5). Flight transportation has significantly higher environmental impacts compared to land transportation (by ∼2 orders of magnitude, tables S6 and S7 of the SI). Therefore, the elevated environmental impacts, comparing imported vs local provision, is estimated as (elevated flight transportation impacts—elevated space heating impacts).

The higher land transport breakeven indicates a longer transportation distance that unit mass (1 ton) of locally produced fish should travel to offset the GWP associated with unit mass (1 ton) of non-locally produced fish. The breakeven analysis using all three space heating scenarios (considering 72 counties in Wisconsin as production points) results in land transport breakeven of 95 358 to 96 987 km, which is ∼7.5 times higher than the Earth diameter. This highlights the environmental advantage of local fish provision over imported fish provision, even considering a cold-weather location production. Additionally, effective space heating results in at least 1223 km higher land transport breakeven compared to ineffective space heating, which is equivalent to ∼0.1 of the Earth diameter. This indicates the importance of improving space heating scenarios for local fish provision in a cold-weather setup to mitigate the environmental impacts of fish provision.

Currently, the majority of studies on fish and aquaculture disregard the environmental implications of transportation due to two main reasons; first, studies are designed as cradle-to-gate analyses, meaning that the system boundary includes life cycle stages up to the production stage. Second, there is potential significant variation in the post-farm processes due to lack of reliable data on the ultimate fate of the products (e.g. no commercialization for research-scale systems). Here we found that neglecting the environmental impacts associated to fish transportation, either land transit or flight, could ignore a significant portion of the total life cycle environmental impacts for fish provision. Hence, expanding on system boundary to include transportation phases is vital for future studies to provide a comprehensive analysis. Furthermore, we found that the increase in local fish provision capacity while elevating systems' environmental performance also requires optimized use of space and location. Implementation of systems in the current unused public infrastructure to provide the required indoor environment for year-round production is one potential approach to undertake for capacity increase. However, effective heating techniques based on the infrastructure configurations (e.g. circulation pattern, solar radiation, etc) need to be executed.

It is relevant to mention that despite considering varying realistic food production and consumption scenarios within this study, there are some associated limitations with respect to the outcomes. This analysis has presented a specific example of fish provision in Wisconsin, employing several case-related calculation steps and data sources. It is vital to conduct further research to reduce the uncertainties for deriving more generic results, and to provide a more comprehensive perspective regarding the environmental implications of food transportation [41, 61, 62]. To extend on the derived results in this analysis, future studies could expand the discussion on (1) comparative spatially-explicit LCA of other food systems in cold-weather regions, (2) the implications of broader geological and temporal variations in production and processing environmental impacts of food provision, and (3) the effects of seasonality and consumer consumption habits to mitigate the environmental impacts of overall food consumption, considering multiple products and dietary norms.

5. Conclusion

We identified that local fish provision, considering (1) all Wisconsin counties as production points, (2) cities of Chicago, Milwaukee, and Minneapolis as consumption points, and (3) effective, semi-effective, and ineffective space heating approaches, has significantly lower environmental impacts than imported fish provision, considering flight transportation from offshore production points. The necessity to elevate local fish production capacity to enhance the environmental sustainability of fish provision is essential, despite potential elevated heating demands for aquaculture in Wisconsin.

Furthermore, we found that (1) elevated heating demands and (2) land transportation have significant contribution to the elevated local fish provision environmental impacts based on varying scenarios (figure 4). In addition, previous research suggests that heating is an environmental impact hotspot in aquaculture, especially in cold-weather regions such as Wisconsin [2, 20]. Thus, practical strategies to improve the environmental sustainability of local fish provision include (1) implementing energy-efficient heating techniques (e.g. effective use of space, passive heating, heater location and configurations), and (2) optimization of fish consumption and production locations according to prospective local demand and production capacity.

Ethical statement

The authors declare no competing interests.

Contributions

Both authors participated in the paper fully. RG and AH designed the modeling, RG performed the modeling and wrote the paper, while AH supervised the projects, edited the paper and gave feedbacks.

Acknowledgment

This paper is based upon work supported by the National Science Foundation (NSF) (Funding No. 1942110). The views presented by the authors have not been formally evaluated by the National Science Foundation and therefore are reflective for the authors' views only. Any brand name products mentioned are for informational purposes only and are not an endorsement. The authors gratefully acknowledge all the colleagues and friends who provided professional advice and spiritual support upon the completion of this work.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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