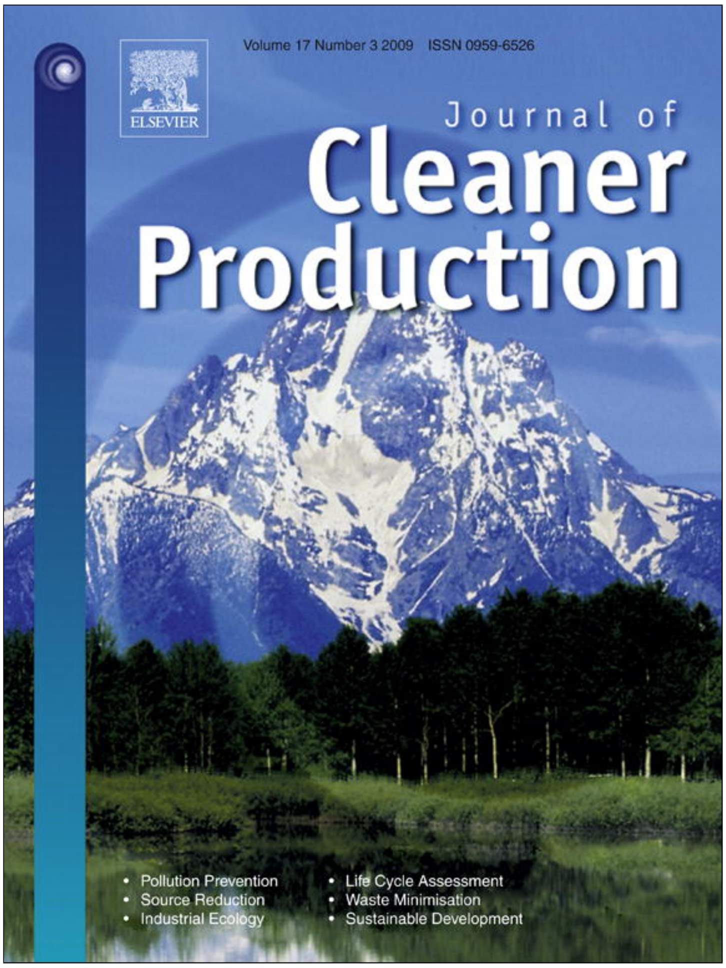
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Isolines as a new tool to assess the energy costs of the production and distribution of multiple sources of seafood

Michael F. Tlusty*, Kerry Lagueux

New England Aquarium, Central Wharf, Boston, MA 02110, USA

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Consumer-based ocean conservation efforts focus attention on seafood that is produced in an "eco-friendly" manner. However, many species can be produced either in aquaculture operations or harvested within wild capture fisheries, and each mode of production differs in their environmental impacts as well as their energy requirements. Complicating the assessment of eco-friendly seafood is the fact that seafood is a global commodity, the suppliers of which utilize a variety of methods to distribute the product from producer to consumer (e.g. ship, truck, airplane). Like the modes of production, these various modes of distribution differ in their energy intensity. This analysis assesses the overall energy requirements of production and distribution ($E_{P\&D}$) of seafood to evaluate how the energy costs of distribution influence the total energy cost of seafood produced by different methods. This paper develops the concept of energy isolines as a tool to assess $E_{P\&D}$. Isolines are a graphical method to succinctly integrate multiple distance assessments so that the best sourcing option can be determined. The isolines are then used to assess how the energy cost of distribution functions as a component of the overall energy cost, and how this influences the $E_{P\&D}$ of a product originating from two different sources with inherently different energy costs of production. Using scallops and salmon as examples, this analysis has revealed that an "eco-friendly" seafood commodity (one produced with less energy) produced far from its destination market could have a higher total $E_{P\&D}$ compared to a local, less "eco-friendly" product (that takes more energy to produce). Finally, this paper evaluates strategies to minimize the overall $E_{P\&D}$ of seafood. Overall, further work on energy audits of seafood focused the need to maintain a global perspective to determine seafood with the lowest overall energy cost of production and distribution.

1. Introduction

Many organizations have designed programs and initiatives to provide consumers with information about "environmentally responsible" seafood (a list of groups can be found at www.seafoodchoices.com). The general goal of these organizations is to enable consumers to make "choices for healthy oceans" by selecting species that are being produced (or harvested) in ways that minimize environmental impacts (including bycatch, habitat damage and overfishing). While such environmental impacts are critical to assess in a life cycle assessment (LCA) and to ultimately minimize, these factors are difficult to reconcile in a wider industrial ecological approach [1]. Industrial ecology focuses on all the life cycle stages as well as on the environmental impacts along the entire production chain, from acquisition of raw materials to trans-national distribution[1] to the consumer [1]. An LCA can look at the "cradle to grave" impact on any of the following categories including abiotic resources, biotic resources, land use issues, global warming, stratospheric ozone depletion, ecotoxicological impacts, human toxicological impacts, photochemical oxidant formation, acidification, eutrophication, and the human work environment [2]. Economic costs are typically not assessed within an LCA because they don't always scale directly to the environmental costs [3]. When both production and distribution are assessed, energy needs are the most parsimonious to use because it is easiest to assess [1]. For the purpose of an integrative assessment of energy

* Corresponding author. Tel.: +1 617 973 6715; fax: +1 617 723 6207.
E-mail address: mtlusty@neaq.org (M.F. Tlusty).

[1] Andersen [1] referred to the movement of product to the consumer as *transportation*. Here, we use the more narrowly defined term *distribution* to indicate this step, as there are numerous other transportation factors associated with the production of seafood. In wild fisheries, the harvested fish must be moved from the fishing grounds to port and then to the processing plant, while in aquaculture, transportation is utilized to describe the movement of fish from hatcheries to grow out sites, as well as getting feed components to the mills, and then to the farms.

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usages, LCA is a useful tool; it seems to be the most reliable [4] and in a broad sense can be indicative of the overall impacts [5,6].

The amount of energy needed to produce seafood varies due to multiple factors including species, production system, and type of food and the energy return on investment extends the gamut from being less to more costly than terrestrial meat production [7]. Seafood production is an increasingly globalized industry and energy intensity is increasing because raw materials and products are being transported over increasing distances [1]. Additional energy use is occurring in fisheries, largely because of overfishing resulting in lower catches per unit effort, as well as causing the fishing fleet to travel farther to more distant fishing grounds This has resulted in a six-fold increase in energy use over two decades to capture the same biomass of fish [8]. Within capture fisheries, different gear types utilize different amounts of energy [7,11]. Because of the plateau in wild fish harvest, but a continuing increase in fish protein demand, aquaculture production has increased to account for nearly 50% of the world's supply of fish [9], although there is concern over this rapid growth [10]. While few LCAs have been conducted on aquaculture operations, results are equivocal, as some have concluded that aquaculture is more energy intensive than the production of fish via a wild fishery [7,11], and livestock systems [4,11], while others have determined the energy return on investment to be lower [12]. Yet it is erroneous to consider all aquaculture operations as having a single unified impact or energy cost. There are many species in production and the key life cycle stage generating most environmental impacts and energy usage is the farming stage [7], largely because of the energy required to produce high-energy, pelleted feeds [13,14]. There is a great deal of variability within a species depending on the type of production system. While some of this is linked to intensive utilization of high-energy pelleted feeds [13], the movement of production into a recirculation facility that requires continual water pumping will also greatly affect the total amount of energy used [11,13,15]. A summary of the energy cost of production for a variety of species and production systems is listed in Table 1.

The concept of food miles was developed to address the environmental impacts of distributing agricultural products [6]. Not all modes of transportation have the same efficiency. In general, the energy cost of distributing products by sea is lower than that of trucking, while air transport is the greatest [6]. Thus, products that are shipped via the oceans will have fewer global impacts than those transported via roads, and both of these will have lower impacts than those transported via air. The assumption from Pirog and Schuh [6] was that the energy cost of production for each product was equivalent, and thus, differences in the energy required to distribute the product was the major factor driving differences in the total energy of production and distribution ($E_{P\&D}$). However, as demonstrated above, seafood production provides a radically different scenario in which the energy required for both production and distribution can vary by multiple orders of magnitude. Since the same seafood item (e.g. a salmon fillet), can be produced in a variety of ways each with a specific and different energy cost, the first part of this paper explores the theoretical differential cost relationship of the energy of P&D ($E_{P\&D}$) for two similar items, one produced with a greater energy expenditure.

The second part of this paper takes this energy cost of production (E_P) difference, and layers on differential energy costs of distribution (E_D). While much of seafood production is exported outside the country of production, the impact of delivering it to a distant market has had little analysis [2]. From a North American perspective, the energy cost of freight could greatly impact best seafood choices, as many of the purported best choices, such as the Marine Stewardship Council's (www.msc.org) certified New Zealand Hoki (*Macruronus novaezelandiae*) and Alaskan salmon (*Oncorhynchus* spp.) are harvested far from the consumer. Both

Table 1
The energy cost (GJ T^{-1}) of aquaculture production systems

Species	Location	System	Energy cost	Source
Carp	Hungary	Constructed fish pond, organic manure	25	[13]
Carp	Hungary	Constructed fish pond, inorganic fertilizer	51	[13]
Carp	Hungary	Constructed fish pond, inorganic fertilizer, supplementary feeding (not pelleted)	77	[13]
Carp	Hungary	Aerated fish pond, high protein feed	87	[13]
Carp	Hungary	Cage culture, high protein food	115	[13]
Carp	Hungary	Recycling system, high protein food	331	[13]
Carp, tilapia, mullet	Israel	Pond	50	[11]
Catfish	Mississippi	Pond	76	[11]
Lake perch, *Perca flavescens*	Wisconsin	Experimental (indoor recirculating)	432	[11]
Mussel		Long line	4	[21]
Oyster	Hawaii	Intensive	152	[11]
Prawn, *Macrobrachium rosenbergii*	Hawaii	Pond	30	[11]
Sea bass	Thailand	Pond	89	[11]
Shrimp	Thailand	Pond	136	[11]
Shrimp, *Penaeus stylirostris* and *Penaeus vannamei*	Columbia	Semi-intensive, pelleted food	129–205	[20]
Rainbow trout	Finland	Net pen	32	[24]
Rainbow trout	Finland	Closed floating cage	55	[24]
Rainbow trout	Finland	Land based marine farm	109	[24]
Salmon – Atlantic	Baltic	Net pen	120–127	[15]
Salmon – Atlantic	Norway	Net pen	24	[4]
Salmon – Atlantic	British Columbia	Net Pen	94	[18]
Salmon – Chinook	British Columbia	Net Pen	117	[18]
Tilapia		Semi-intensive	24	[21]

have culinary equivalents produced closer to the ultimate consumer. Because of the differential costs of production and distribution, we use the concept of energy equivalency, or an isoline on a two-dimensional map, to relate the intrinsic energy cost of production, as well as the mode influenced energy cost of distribution for two seafood products that are equitable in the market place, but produced differently. Here we focus on the dilemma of what the total energy cost is of a seafood product that requires less energy to produce, but originates farther from a consumer than a closer, yet more energy costly product. This case is illustrated using the examples of both Atlantic scallops, *Placopecten magellanicus*, and Atlantic and Pacific salmon, *Salmo salar* and *Oncorhynchus* spp. The converse situation, comparing a product produced close to the consumer with relatively less energy efficient production to a farther, more energy costly product, is considered trivial because in this case, the local product will have a lower total energy of production and distribution. This analysis concludes with assessing local and global seafood production schemes, and an attempt to derive some organizing principles to continue to advance the positive steps being taken toward energy efficient seafood production.

2. Methods

This paper assesses the relative contribution of distribution in the overall energy cost of seafood products, first, theoretically, and second by assessing the energy cost of production from values reported in the literature. This is not meant to be a *de novo* LCA for any seafood item, but rather, it takes published examples of energy requirements for producing seafood, and provides a tool to conduct a more complete investigation of the energy necessary to produce *and* deliver the product to the consumer. Within the theoretical treatment, the $E_{P\&D}$ was first assessed when there were two different energy costs of production, with one being less than the other ($P < P'$), but the distribution mode is the same. The result for this analysis was output as Δ, the distance differential, which was defined as the distance in which $P + D = P'$, and functionally defined how far apart two centers of production could be so that the cheaper (P) could be shipped to the more expensive (P') for less total energy. This relationship was assessed for both air and truck distribution for values of P from 2 to 50 GJ T^{-1}. In general, the energy required for seafood production ranges from 2 to 358 GJ T^{-1} [7]. The values of P' were assessed at 2 and 5 times the value of P.

The question of "*is there any case in which a more energy expensive seafood product shipped with a less energy intensive mode of transport is a lower* $E_{P\&D}$ *option compared to the alternative?*" was then addressed. The differing energy costs of production were layered with the constraint that the product with the lower energy cost of production (P) was air shipped (14 MJ T^{-1} km^{-1}), while the product with the greater energy cost of production (P') was distributed via truck (3 MJ T^{-1} km^{-1}) [16]. In this case, x, the energy isoline, or the point at which $E_{P\&D}$ of P and P' is equivalent, will be set as the pointwhere x is the distance P is shipped via air, and K is the total distance (km) between P and P'. In the theoretical example discussed within, K is set as 4800 km, the distance between the important seafood ports of Seattle WA on the west coast of the continental US, and its east coast equivalent, New Bedford MA.

Two case studies are then explored using published energy audits of specific fisheries, wild Atlantic sea scallops, *P. magellanicus*, harvested in the US and in Canada; and Atlantic salmon (*S. salar*) produced in aquaculture in New Brunswick, Canada compared to Pacific salmon (*Oncorhynchus* spp.) harvested in Alaska. The fisheries were chosen because they are produced in disparate areas with different technologies resulting in different energy inputs. Also, they can both be transported via truck or air.

For any one location, the most environmentally responsible choice in terms of energy use is the source with the lowest calculated energy cost of production and distribution ($E_{P\&D}$). To assess this, we determined the $E_{P\&D}$ of each of the seafood sources distributed both by air and truck, and compared the alternatives. The four comparisons included the first source distributed by truck (P_T) compared to the second source distributed by truck (P'_T); both distributed by air (P_A vs. P'_A), and one by truck and one by air (P_A vs. P'_T, and P_T vs. P'_A). Distance calculations were determined using ArcGIS® 9.2 GIS software using a Two Point Equidistant project to ensure proper calculations between the two cities in question. We used differing parameters for the projections based upon the coordinates of the two cities. Air Travel used straight line distance calculations which resulted in cell based data layer of distance radiating from the input city. Road distance was calculated using a straight line distance multiplied by a modifier based upon the highway network. The distance modifier for the road network was based upon the average difference in straight line distance and the road distance between five cities geographically dispersed in the United States. The energy cost of production and shipping were then calculated for each production–distribution combination, and the different sources are compared against each other using the distribution specific values. When the differential = 0, this demarcated the energy isoline where $E_{P\&D}$ of the two sources were equivalent. Graphically, this was represented as an isoline on a map, and differentiated the distance at which there was a switch in the lower energy option. Hence, alternative P is the lowest energy option for any location between the point of production and the isoline, while alternative P' has a lower $E_{P\&D}$ on the opposite side of the isoline. If no isoline exists, then it is the case where the lower energy production method is a still lower energy option than the second source, even after the distribution energy has been added to the total.

3. Results

3.1. Differing energy costs of production and the $E_{P\&D}$

The energy cost of production of seafood is measured in GJ while transportation is measured in MJ. Thus, as the energy cost of production increases, the influence of distribution on the overall $E_{P\&D}$ will decrease (Fig. 1). Distribution modes utilizing less energy per unit *km (e.g. road freight) naturally account for a smaller percent of the total $E_{P\&D}$ than more expensive modes such as air freight.

The value Δ represents how far a lower energy cost product can be distributed before it equals the energy required to produce the second product ($P + D = P'$). Δ increased with the base energy cost of production P, an intuitive result since the energy cost of production is orders of magnitude larger than the energy required for distribution. For any production cost P, Δ is greatest when truck distribution is used compared to air distribution (Fig. 2). But the overall effect also depends on the relative value of P' compared to P. Thus, Δ is greater when P' is twice as large as P and the product is distributed via road, compared to if P' is five-fold as great as P, but the product is distributed via air (Fig. 2).

While Δ is instructive for assessing changes in the overall $E_{P\&D}$, it is rare that the two production locals will be at the same geographic location. More commonly, centers of production will be distributing to a market location intermediate to the sources. In this case, the energy equivalency will be an isoline between the sources in which $P + D = P' + D'$. As a theoretical example, consider a product costing 2 GJ T^{-1} to produce originating in Seattle and being distributed by air. A more costly product ($P' = 2P$ or $5P$) originates in New Bedford 4800 km away and is distributed by truck. Under this scenario (Fig. 3), isolines occurred ~1000 km from P when P' was 2× greater, and ~1500 km when P' was 5× greater (Fig. 3 bottom). However, if P increased to 20 GJ T^{-1}, then the isoline for $P' = 2P$ doubled to ~2000 km, but when P' was five-fold larger than P, there was no isoline since for all cases <4800 km, $P + D < P'$. The

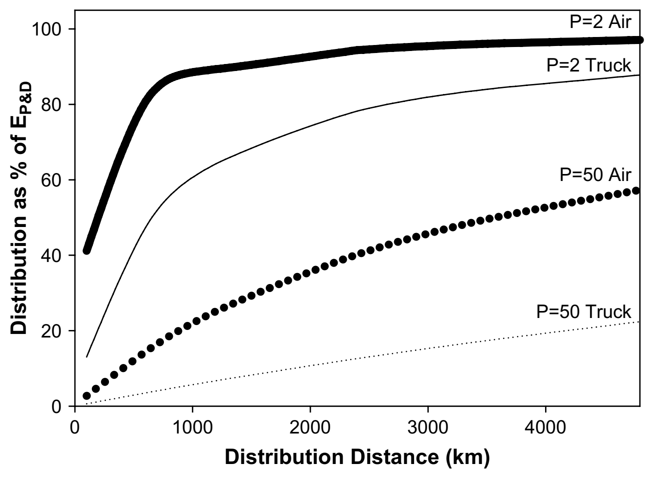

Fig. 1. The relative contribution of distribution to the total $E_{P\&D}$ as a function of distribution mode and cost of production. As the distance seafood is shipped increases, the greater the contribution of distribution to the total $E_{P\&D}$. The contribution is larger when production costs are 2 GJ T^{-1} (solid lines) compared to 50 GJ T^{-1} (dotted lines), and for distribution by air (thick lines) compared to truck (thin lines).

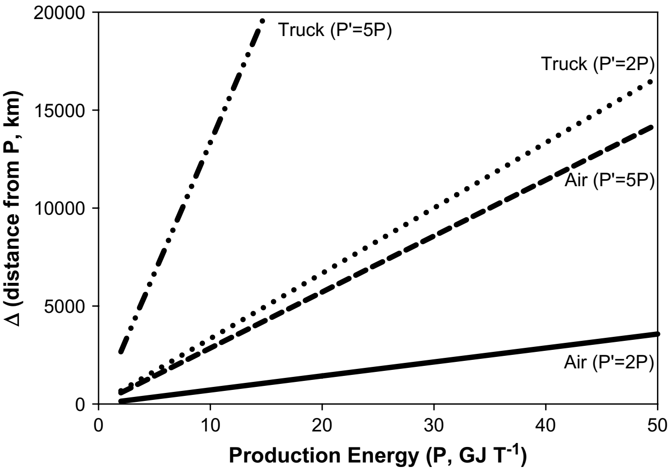

Fig. 2. The differential distance Δ that a product from P can be distributed so that $E_{P\&D}$ of $P = P'$. The value of P is on the x axis, and P' is 2 or 5 times larger. Δ increases as the cost of production increases, as the relative value of P' increases with respect to P, increases more rapidly when the product is distributed by truck as compared to air. As a reference, the distance from New Bedford MA to Seattle WA is approximately 4800 km.

overall result of these theoretical examples was that there is no simple rule of thumb such as "choose local" or "choose road over air". The lowest $E_{P\&D}$ is a multifactoral problem depending on the production energy cost and distribution mode of each product, as well as the total distance each has to travel.

Using the principles just developed, two cases will be explored with Atlantic scallops, and salmon.

3.1.1. *Case study 1: Atlantic sea scallops*

Atlantic sea scallops are typically harvested by dredge fishing from sandy and cobble bottom habitats in the western Atlantic

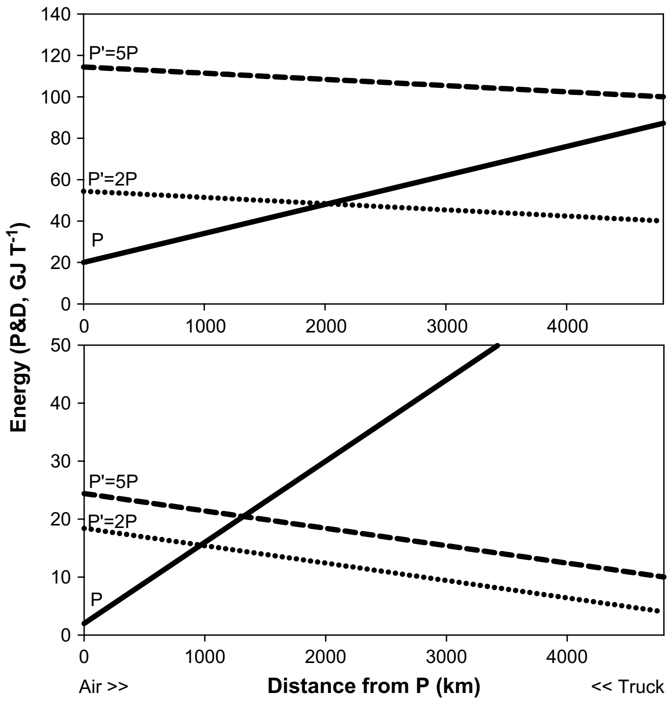

Fig. 3. The $E_{P\&D}$ for seafood products produced in two locations 4800 km apart. The product from P is distributed by air, while P' is distributed by truck. P' is two (thin dotted line) and five times (thick dotted line) as costly as P, respectively, where $P = 2$ GJ T^{-1} (bottom) and 20 GJ T^{-1} (top). As the base cost of production increases, the implication of the alternate source having a relative larger production cost is much greater.

Ocean. Scallops are harvested in both the US (represented by New Bedford, MA), and Canada (Halifax, NS). In 1999, 12.9 GJ T^{-1} of energy were required to harvest scallops in the Canadian fishery [8]. However, since that time, the Canadian fishery financed sophisticated bottom habitat mapping, which allows fishing vessels to avoid unproductive areas. As a result, the Canadian scallop industry has reduced fuel usage by 36% while maintaining harvest levels [17]. Since direct fuel energy is 75–90% of the total energy input in a fishery analysis, it is assumed that the Canadian scallop industry operates with 64% the energy of the US fishery. Thus, the energy intensity of the present-day Canadian Scallop fishery is estimated to be 8.25 GJ T^{-1} (P_{Can}), while that of the New Bedford fishery remains at 12.9 GJ T^{-1} (P_{US}). With these energy costs of harvest, different freight scenarios can now be explored. The GIS analysis indicates that Δ for Canadian scallops distributed by truck is 1550 km. In other words, the distance at which the energy of production (P_{Can}) and distribution (T_{Can}) for Canadian scallops equals that of US production (P_{US}) is 1550 km. Since the port of New Bedford is closer to Canadian ports than 1550 km, trucking Canadian harvested scallops will always be the lowest energy alternative. It likewise follows that any ocean freight of scallops (Halifax to Portland, Maine or Boston, MA) would also be less costly than P_{US}.

However, freshness and immediacy of distribution are important factors in marketing seafood, and thus long distance truck freight is often not feasible making air freight necessary. Considering air freight of Canadian harvested scallops, $CAN_A > P_{US}$ indicating that there is an energy equivalency line between the two source locations. The two energy isolines for CAN_A:US_T and CAN_A:US_A are shown in Fig. 4. Because of the higher energy cost of air freight, the CAN_A:US_A isoline is closer to New Bedford than the CAN_A:US_T isoline. This means that for a city such as St. John, New Brunswick, CAN_T is the lowest energy, then in increasing order is CAN_A, US_T and finally US_A. Major markets in the continental US and Southern Canada have the energy efficiency order of $CAN_T < US_T < US_A < CAN_A$, while northern Canada has a slightly different order ($CAN_T < US_T < CAN_A < US_A$). The truck freight of Canadian harvested scallops is the overall lowest $E_{P\&D}$, but timing and quality issues may prevent this from being a viable option. If it is impossible to truck scallops, then the relatively lowest $E_{P\&D}$ for the continental US is US_A, while for northern Canada and Alaska, it is CAN_A.

3.1.2. *Case study 2: salmonids*

The aquaculture production of Atlantic salmon (*S. salar*) rose to prominence in the 1980s as a response to declining wild harvests. The main locations of Atlantic salmon aquaculture include Canada (both coasts), Chile, Norway, and the UK. Although aquaculture-produced Atlantic salmon and wild harvested Pacific salmon (*Oncorhynchus* spp.) are quite different in terms of quality, consistency and taste, they are often touted as being alternatives in seafood marketing endeavors. The largest Pacific salmon fisheries occur in Alaska, and typically ship out of Anchorage. For comparison of how modes of shipping influence total energy cost of production, the disparately located aquaculture production area of New Brunswick (St. John) will be considered. While the calculated energy costs for production of Atlantic salmon in aquaculture vary (Table 1), the values of Tyedmers [18] are used because of the uniformity in energy calculations that comes from a single authored study. The lowest estimate of energy cost of salmon aquaculture [4] comes from a study that did not assess capital goods such as buildings and vehicles.

Intensive cage farming of Atlantic salmon uses 94 GJ T^{-1} of energy [18], while troll caught Pacific salmon are produced with 34 GJ T^{-1}, and purse seined Pacific salmon with 17 GJ T^{-1} (data from BC Canada, assumed to be valid for Alaska, 12). The energetic cost of purse seined salmon is so low that it can be trucked or flown from

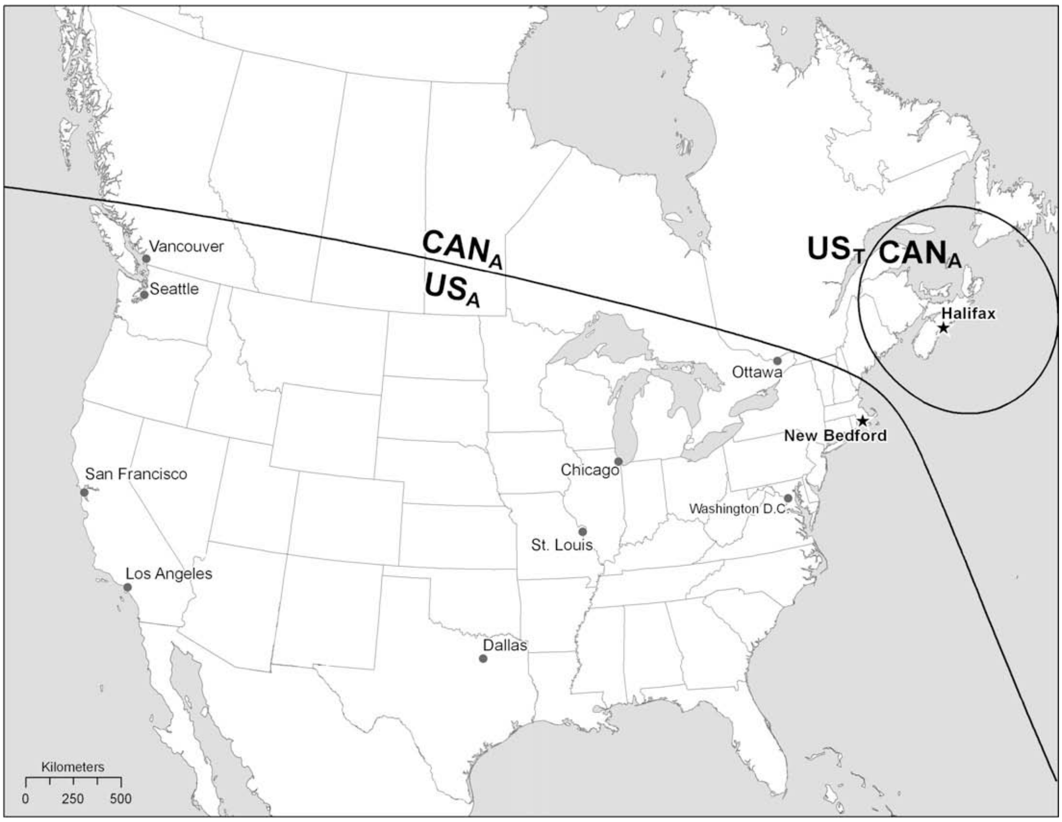

Fig. 4. Isolines defining the locations where energy costs are equivalent for the paired comparisons of air freighted Canadian Atlantic scallops to those truck or air freighted from the US. CAN scallops can be truck freighted to New Bedford for less energy than that needed to produce scallops there, and thus there is no CAN_T isoline.

Anchorage (P-ANC_T, P-ANC_A) to St. John, NB (STJ) for less energy than what it costs to produce an equivalent amount of Atlantic salmon in aquaculture. However, for troll caught salmon, a similar pattern emerges, as was observed in scallops. Troll caught Pacific salmon can be truck freighted from Anchorage (T-ANC_T) to STJ for less energy that what it costs to produce salmon in aquaculture. When air freight of troll caught salmon is considered, there is an energy isoline between ANC and STJ (Fig. 5). In the case of salmon, the isoline comparing air freight of troll caught wild salmon from Anchorage (T-ANC_A) and truck freight of STJ farmed salmon A-STJ_T is just to the east of Chicago, St. Louis, and Dallas indicating that T-ANC_A is the better $E_{P\&D}$ option for these cities and those to the west. When comparing air freight of both salmon alternatives (T-ANC_A, A-STJ_A), the isoline moves east proportional to the changes in the energy cost of transportation.

Other sources of both wild caught Pacific salmon, and aquacultured Atlantic salmon exist. There are sizeable Pacific salmon troll fisheries on the west coast of the United States in Oregon and Washington State that are closer options than Alaskan salmon. These fisheries harvest salmon with 82–87 GJ T^{-1} [19, data in 7], which is significantly more energy than that utilized by the Alaskan fishery. This increase in the energy cost of production offsets the smaller travel distance, and in comparing troll caught Pacific salmon from Seattle (T-SEA) to A-STJ, four isolines are observed. The isolines are ordered west to east as the energy of distribution from each source changes (Fig. 5).

For aquacultured salmon, Chile is a major supplier to North America, where the Chilean salmon are air freighted to Miami, and subsequently distributed from there. The distance of Chile to North America coupled with the reliance on air freight, makes it a larger energy intensive alternative than either Anchorage wild salmon or St. John farmed salmon. The isolines for comparisons of air freight of Chilean salmon to air freight of the two North American alternatives are located in the northern part of South America. However, sea freight of Atlantic salmon from Chile would be an energy viable option when compared to A-STJ, but not the pacific wild fisheries. Valdivia, Chile is 5076 nm (9041 km) from Los Angeles (LAX). The energy required to sea-freight salmon this distance is 0.56 MJ/t-km, or 5.0 GJ T^{-1} making Chilean salmon landed in LAX 100 GJ T^{-1}. However, T-SEA can be trucked to LAX for the same distribution energy cost, making this still the more energy efficient option. The overall energy budget of Chile needs to be directly assessed prior to any further speculation. In some instances, LCAs of salmon [4] and trout [26] calculated energy requirements more similar to the values used here for the wild fishery (see Table 1). Chile is close to the sources of fishmeal and oil, and that plus the specific patterns of vegetable substitution and co-allocation [23] will determine the overall energy budget.

The type of product that is being shipped will also affect the overall energy audit. The above analysis was conducted on the round weight of fish, and for the comparison of T-ANC_A to A-STJ_T, the distribution energy costs were 64% and 5% of the total $E_{P\&D}$, respectively. When the production energy costs are more similar, the energy allocation of production and distribution also become more similar. In the example of comparing T-ANC_A to A-STJ_T, a 10 GJ T^{-1} decrease in P_{STJ} to 84 GJ T^{-1} would result in distribution values (as a % of the total) of 61% and 8% for T-ANC_A and A-STJ_T, respectively. This 10 GJ T^{-1} decrease in the overall E_D by a similar amount, and would shift the isoline to the west 561 air km and 713 road km. If energy costs of production are more similar, such as the T-SEA_A and A-STJ_T values, distribution follows the same trend, and accounts for 30% and 17% of the total energy costs, respectively.

A great deal of the salmon enters the US as a fillet, which is 60% of the round weight. If the distribution energy cost is likewise

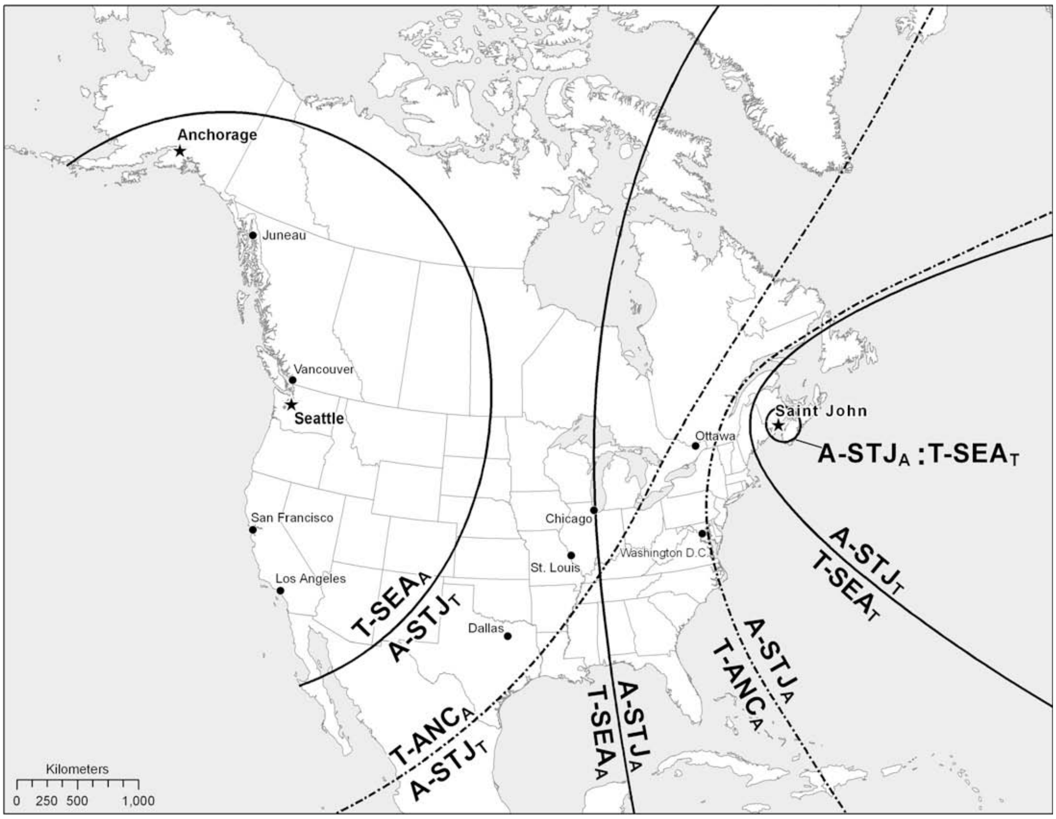

Fig. 5. Isolines defining areas where the energy costs are equivalent for the paired comparisons of aquacultured Atlantic salmon to troll caught wild caught Pacific salmon from Alaska (T-ANC, dashed line) or the West Coast US (T-SEA, solid line). Purse seined ANC, and truck freighted T-ANC salmon cost less energy to ship to STJ than fish produced there in aquaculture, and thus there are no P-ANC$_T$, P-ANC$_A$, or T-ANC$_T$ isolines.

reduced to 60%, the $E_{P\&D}$ to deliver T-ANC$_a$ to St. John NB is reduced to 81 GJ T^{-1} which is less than the cost of production of farmed salmon (Fig. 6). Thus to be competitive on an energy basis, the overall energy requirements of aquacultured salmon would need to be reduced by more than 18 GJ T^{-1}. A similar shift is observed with salmon from Seattle. If trucked, the reduction in freight shifts the curves established in Fig. 5 so that salmon can be distributed to St. John for less total energy than that necessary to grow the salmon in aquaculture. Air freight is more energy intensive, and thus the isoline moves to the east, but does not envelope St. John (Fig. 7). Production is the energy intensive step in determining $E_{P\&D}$, and because of this, processing has the effect of decreasing shipping weights resulting in a net overall shift of the isoline toward the seafood source that requires more energy for production.

4. General discussion

The concept of food miles was introduced for agricultural products to provide consumers with a relative indicator about the transport-related environmental impact of their purchases [6]. However, as demonstrated within, selecting a lower energy option between two seafood sources is a bit more complex because the overall energy comparison, and subsequent environmental impact, depends on both production and distribution energy costs. Unfortunately, there is no simple message to deliver regarding large scale trends in $E_{P\&D}$. While the closer source is the often better decision in terms of $E_{P\&D}$, there are cases where a product produced farther from the market but with a lower production energy cost has the lower $E_{P\&D}$. Overall, the energy cost of production, relative difference in production costs between sources, and mode of distribution all need to be assessed to determine the source with the lowest $E_{P\&D}$.

This analysis was not intended to be a definitive assessment of the $E_{P\&D}$ of scallops and salmon. These case studies were used to describe isolines, a new tool to interface life cycle assessments into a GIS based framework. Isolines are a graphical method to succinctly integrate multiple distance assessments so that the best

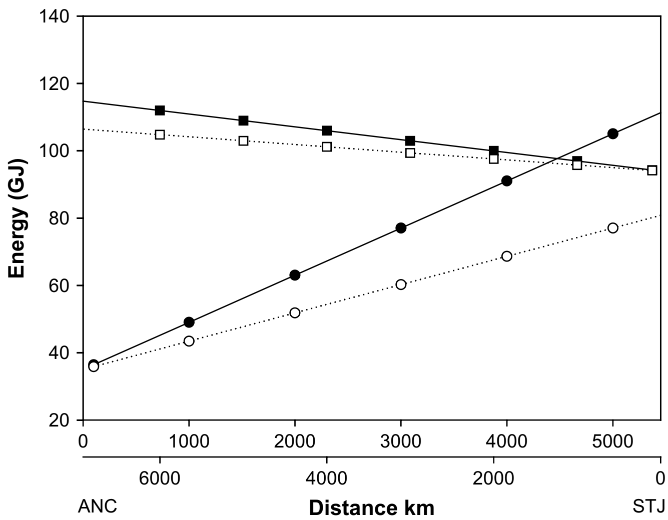

Fig. 6. The energy cost of production and distribution for whole (closed symbols) or fillet (open symbols) Atlantic salmon via air from Anchorage (troll fishery, circles) or by truck from St. John NB (aquaculture, squares). The two x-axes indicate the distance via air for ANC-STJ (top) or road from STJ-ANC (bottom). The point at which the ANC and STJ lines cross indicates energy equivalency for the different production and distribution methods. Air freight of fillets instead of whole salmon from Alaska will decrease the energy of production and distribution to a point where it is of lower energy than aquaculture production.

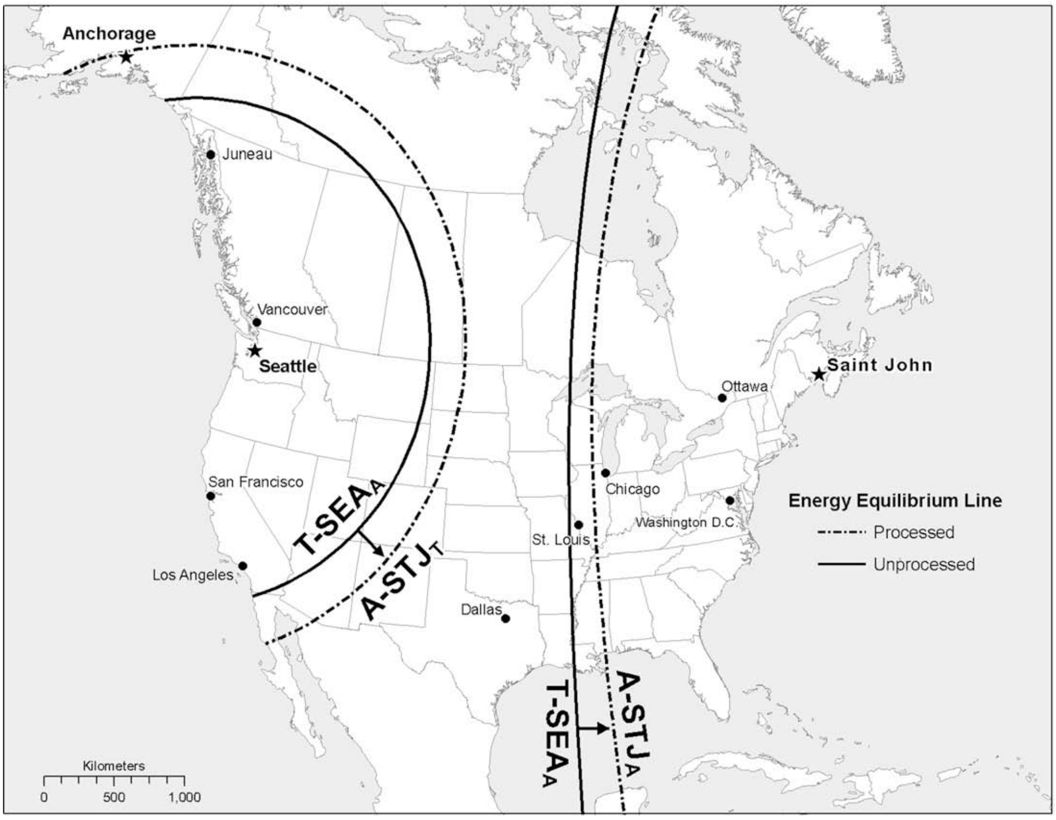

Fig. 7. The effect of processing on the $E_{P\&D}$ isolines. Decreasing the relative shipping weight shifts the isoline toward the seafood source with the greater cost of production. Here, round (unprocessed) and fillet (processed, 60% weight of round) salmon wild caught from Seattle (air and truck distribution) is compared to truck distribution of aquaculture product from St. John NB.

sourcing option can be determined. Furthermore, it demonstrates that a production system that has energy costs nearly three times that of the alternative, as did the example of farmed compared to wild salmon, can compete energetically for markets given traditional distribution methods. However, it should be noted, that the 94 GJ T^{-1} is likely to be an overestimate (Tyedmers, personal communication), and newer estimates demonstrate lower energy values [4].

This isoline method will be valuable for other food assessments, because there are multiple cases where alternative products have drastically different energies of production. Recent work on agricultural products indicates that apples may have an order of magnitude difference in production energy, with the upper limit of production energy being 3.8 GJ T^{-1} [20]. For seafood, catching salmon with a purse seine utilizes less energy than catching them via trolling [12], while wild harvested shrimp (U.S. average 150 kcal/kcal shrimp protein [11] which is equivalent to 678 GJ T^{-1}) is nearly three times that of a typical aquaculture production [21]]. In fact, many aquaculture species, including mussels, carp and tilapia are among the most energy efficient species grown or harvested for protein. These species have some of the highest energy returns on investment (EROI) of edible protein of seafood or agriculture products [7]. Unfortunately, because the base production energy cost was one of the factors that determined the positioning of the isoline, EROI cannot simply be back-calculated to include distribution energy. Adding distribution costs into the EROI will lower this value, but the degree to which it is lowered will depend on the energy cost of production. If all the alternatives have an EROI of 50% and are air freighted 1000 km, the EROI adjusted to include distribution will decrease to 6% if the production is 2 GJ T^{-1}. When production requires 20 GJ T^{-1}, the adjusted EROI will only decrease to 29%.

With aquaculture's growing in importance in the future production of adequate amounts of protein, there are proactive steps that can be taken to ensure it develops in an energetically responsible manner. Emphasis on increased development needs to be placed on the energy efficient species such as the carp, mussels, and tilapia. These species are energy efficient because they do not rely on high-energy pelleted feeds, or if fed such a feed, it has a lower inclusion of fishmeal and oil than salmon feed. Feed is a significant energy component of aquaculture production [14,22]. The energy cost of salmon feed can be reduced by nearly 75% if vegetable-based meals and oils are used instead of fish-based [4]. Thus, even with salmon farming, there is room for improvement in energy efficiency through vegetable-based feeds, recycled meal and oil, or use of co-products [23]. Folke and Kautsky [24] identified integrated aquaculture for both ponds and ocean-based production as a means to improve the energy transfer and ecosystem functioning of aquaculture production. Their ocean-based example includes polyculture of seaweed, mussels, and salmon. The analysis presented within utilized the Tyedmers [18] value of 94 GJ T^{-1} for aquaculture salmon production. This value was medial to other values for salmon ranging from 24 [4] to 124 GJ T^{-1} [15]. Thus a large need to advance this field is to reconcile the difference in energy utilization for different aquaculture production systems, as this value will greatly affect the final location of the $E_{P\&D}$ isoline.

Because pond-based carp and tilapia culture, and long-line mussel production are relatively low energy input systems, they will be greatly affected by distribution miles. Thus, these species have high potential to be integrated into a locally grown "seafood miles" program. However, such a program must be undertaken carefully, because production is the dominant factor in an $E_{P\&D}$ analysis [25]. While there is nothing in principle that prevents air freight of seafood, it is not consistent with the concept of ecological sustainability [1]. Thus seafood produced half-way around the globe, and distributed via sea may have a lower $E_{P\&D}$ than a locally produced item. As demonstrated above with salmon from Chile, ocean freight will add very little to the overall energy cost of the product, and the distant production need to be only 5 GJ T^{-1} more efficient than the local product be a lower energy option. With much aquaculture occurring in India (Jakarta to Los Angeles 7355 nm), and China (Hong Kong to Los Angeles 6379 nm), the energy cost of local production (Δ) can exceed that of distant production by only 7.6 or 6.6 GJ T^{-1}, respectively. If local production is more energy intensive than this, then the distant source will be the best energy option. Relying on ocean freight virtually mandates that frozen product is distributed. Of note is that the significant energy requirement of freezing a product is in the initial chilling to cold storage temperatures. Thus the differential energy cost between a chilled and a frozen product are minor. It is within reason that the most energy efficient seafood may be produced half-way round the globe, frozen, and ocean freighted.

Recirculation technology is being advanced as being a method to bring aquaculture production local, particularly in northern climes. However, assessments for trout [26] and carp [13] indicate that energy costs nearly tripled when production was moved into a recirculation facility. In addition, recirculation production did not offer a benefit in terms of environmental impacts of reduced nitrogen or phosphorus output [26]. While a simple $E_{P\&D}$ analysis does not rule out this option, energy is a large production cost to overcome merely through local distribution.

The choice of the most environmentally friendly seafood is a difficult choice, as there are many different methods to measure how "eco-friendly" a particular product is. Analyzing the energy cost of production and distribution is a useful tool, as it allows for a single method to compare the different practices used to produce and then deliver the seafood product to the consumer. In this analysis, it became apparent that seafood sourcing is not always better merely conducted on a regional scale. Although the freight energy cost to distribute seafood is orders of magnitude less compared to the energy cost of production, it is still significant enough to alter the amount of energy needed to produce seafood in disparate locations and distribute throughout the distribution chain. However, as the difference in energy costs for production increases, the energy of distribution will have less of an impact on the total energy budget.

The distance disparity of production location for many seafood products makes it difficult to identify a single best seafood option for all locations. Thus, "eco-friendly" seafood campaigns need to maintain a global focus to properly educate consumers about the full impacts of their seafood choices. This analysis of $E_{P\&D}$ is an extension of LCAs, and this work needs to be assessed as preliminary because of the limited number of LCAs of industrial fisheries and aquaculture [2]. It is critical that more complete analyses of LCA are conducted for seafood as this will allow for more accurate energy assessments to be made. It is also critical to achieve a better understanding of global seafood distribution chains, including the decision point for switching from truck to air freight for shorter hauls, and the overall role of ocean freight. In addition, it is unknown here if backhaul journeys are significant for seafood, and thus, were assumed to not enter into the equation. Logistics providers often service multiple distribution networks, as the assumption was that the providers optimize their capacity and efficiency in backhauls to increase profitability [25,27]. These ventures will be a worthwhile as one benefit of a LCA is that the energy cost of remediating environmental impacts can be assessed and integrated into the energy cost of production, further unifying the comparison of different seafood production systems.

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References

[1] Andersen O. Transport of fish from Norway: energy analysis using industrial ecology as the framework. J Clean Prod 2002;10:581–8.
[2] Pelletier N, Ayer N, Kruse S, Flysjo A, Robillard G, Ziegler F, et al. Impact categories for life cycle assessment research of seafood production: review and prospectus. Int J LCA 2007;12(6):414–21.
[3] Norris GA. Integrating life cycle cost analysis and LCA. Int J LCA 2001;6(2): 118–20.
[4] Ellingsen H, Aanondsen SA. Environmental impacts of wild caught cod and farmed salmon – a comparison with chicken. Int J LCA 2006;11(1):60–5.
[5] Thrane M. LCA of Danish fish products: new methods and insights. Int J LCA 2006;11(1):66–74.
[6] Pirog R, Schuh P. The load less traveled: examining the potential of using food miles and CO2 emissions in ecolabels. Presented at Ecolabels and the Greening of the Food Market, Boston MA; 7 November 2002. Available from: <www.leopold.iastate.edu/pubinfo/paperspeeches/The_load_less_traveled.pdf>.
[7] Tyedmers P. Energy consumed by North Atlantic fisheries. Fish Cent Res Repo 2002;9(3):12–34.
[8] Mitchell C, Cleveland CJ. Resource scarcity, energy use and environmental-impact – a case-study of the New Bedford, Massachusetts, USA, fisheries. Environ Manage 1993;17:305–17.
[9] FAO Fisheries Department, State of World Aquaculture. FAO fisheries technical paper, No. 500. Rome: FAO; 2006. 134 pp.
[10] Naylor R, Goldburg R, Primavera J, Kautsky N, Beveridge M, Clay J, et al. Effect of aquaculture on world fish supplies. Nature 2000;405:1017–24.
[11] Pimentel D, Shanks RE, Rylander JC. Bioethics of fish production: energy and the environment. J Agric Environ Ethics 1996;9:144–64.
[12] Tyedmers P. Fisheries and energy use. In: Cleveland C, editor. Encyclopedia of energy, vol. 2. San Diego, CA: Academic Press/Elsevier Science; 2004. p. 683–93.
[13] Olah J, Sinha VRP. Energy cost in carp farming systems. FAO project report AC225/E; 1986. Available from: <www.fao.org/docrep/field/003/AC225E/AC225E00.htm>.
[14] Papatryphon E, Petit J, Kaushik SJ, van der Werf HMG. Environmental impact assessment of salmonid feeds using life cycle assessment (LCA). Ambio 2004;33:316–23.
[15] Folke C. Energy economy of salmon aquaculture in the Baltic Sea. Environ Manage 1988;12(4):525–37.
[16] Murtishaw S, Schipper L. Energy savings and structural changes in the U.S. economy: evidence from disaggregated data using decomposition techniques. Berkeley, CA: Lawrence Berkeley National Lab; 2001. LBNL-48786.
[17] Taylor PH. Mapping the undersea landscape: using seafloor maps to improve management of the Gulf of Maine. So, Portland, ME: Gulf of Maine Council on the Marine Environment; 2003.
[18] Tyedmers P. Salmon and sustainability: the biophysical cost of producing salmon through the commercial salmon fishery and the intensive salmon culture industry. Ph.D. thesis University of British Columbia; 2000.
[19] Rawitscher MA. Energy cost of nutrients in the American diet. Ph.D. thesis, The University of Connecticut; 1978.
[20] Canals ML, Cowell SJ, Sim S, Basson L. Comparing local versus imported apples: a focus on energy use. Environ Sci Pollut Res 2007;14(5):338–44.
[21] Larsson J, Folke C, Kautsky N. Ecological limitations and appropriation of ecosystem support by shrimp farming in Columbia. Environ Manage 1994;18:663–76.
[22] Troell M, Tyedmers R, Kautsky N, Rönnbäck P. Aquaculture and energy use. In: Cleveland C, editor. Encyclopedia of energy, vol. 1. San Diego, CA: Academic Press/Elsevier Science; 2004. p. 97–107.
[23] Ayer NW, Tyedmers PH, Pelletier NL, Sonesson U, Scholz A. Co-product allocation in life cycle assessments of seafood production systems: review of problems and strategies. Int J LCA 2006;. doi:10.1007/s11367-006-0284-2.
[24] Folke C, Kautsky N. Aquaculture with its environment: prospects for sustainability. Ocean Coast Manage 1992;17:5–24.
[25] Weber CL, Matthews HS. Food-miles and the relative clomate impacts of food choices in the United States. Environ Sci Technol 2008;. doi:10.1021/es702969f.
[26] Grönroos J, Seppälä J, Silvenius F, Mäkinen T. Life cycle assessment of Finnish cultivated rainbow trout. Boreal Environ Res 2006;11:401–14.
[27] Sim S, Barry M, Clift R, Cowell SJ. The relative importance of transport in determining an appropriate sustainability strategy for food sourcing. Int J LCA 2007;12(6):422–31.