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Energy prices and seafood security

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ABSTRACT

Fish resources are critical to the food security of many nations. Similar to most contemporary food systems, many fisheries and aquaculture resource supply chains are heavily dependent on fossil fuels. Energy price increases and volatility may hence undermine food security in some contexts. Here, we explore the relationships between energy price changes, fish resource supply chain viability, seafood availability and food security outcomes – both for producers and consumers of fish resources. We begin by characterizing the energy intensities of fish resource supply chains, which are shown to be highly variable. We subsequently assess the comparative magnitude and distribution of potential food security impacts of energy price increases for nation states by scoring and ranking countries against a set of vulnerability criteria including metrics of national exposure, sensitivity and adaptive capacity. Considerable variability in the vulnerability of populations and high levels of exposure for already food-insecure populations are apparent. Developed countries are likely to be most exposed to the effects of energy price increases due to their high rates of fleet motorization and preference for energy-intensive seafood products. However, heavy reliance on seafood as a source of food and income, as well as limited national adaptive capacity, translates into greater overall vulnerability in developing countries. At the level of individual producers, a variety of adaptation options are available that may serve to reduce vulnerability to energy price changes and hence contribute to increased food security for producers and consumers, but uptake capacity depends on numerous situational factors.

1. Introduction

Increasing energy prices and energy price volatility are becoming hallmark characteristics of the global economic system (Hall and Klitgaard, 2006; Weller and Fields, 2011). Contributing factors include: declining availability of easily accessible fossil fuels and associated geopolitical tensions; climatic instability and related natural disasters that impact on energy infrastructure; and the inter-linkages between energy-dependent economic growth, population growth, and changing consumption patterns toward more energy-intensive lifestyles (Hall and Klitgaard, 2006; Baffes, 2007; Pelletier et al., 2011). In light of the energy-intensity of contemporary food systems, the implications for food security merit closer attention (Pollan, 2006; Neff et al., 2011; Pelletier et al., 2011).

Food security refers to a state of universal "physical, social and economic access to sufficient, safe and nutritious food that meets dietary needs and food preferences for an active and healthy life" (FAO, 2002). Stability of supply and accessibility are two key components of food security. Stability of supply – whether from domestic food production or imports – is influenced by price volatility (Nellemann et al., 2009). Price volatility often motivates producers to use poor investment strategies because formulating rational plans for the future is confounded by uncertainty (Weller and Fields, 2011). In turn, sub-optimal investment strategies undermine food supply stability. Accessibility is often largely determined by affordability. This is of particular concern in developing countries, where a disproportionate share of income – 50–80% in the most impoverished households – is allocated to food

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purchases (Nellemann et al., 2009; FAO, 2011a). In such contexts, a doubling of food prices – as was seen during the 2008–2009 food price spikes – has severe impacts on food accessibility. The predicted rising trend in food prices over the next decade is, in this light, particularly concerning vis-à-vis food security outcomes (OECD-FAO, 2012).

Food prices are determined at the intersection of multiple factors (Abbot et al., 2008; Mitchell, 2008; Gilbert and Morgan, 2010). In counterpoint to the historical downward trend in real food prices due to productivity gains and trade-induced competition, recent food price hikes have been strongly influenced by rising energy costs (Deike et al., 2008; Goldman Sachs, 2008; Mitchell, 2008; Piesse and Thirtle, 2009). Food sector energy use accounts for roughly 32% of global energy use (FAO, 2011a). Nellemann et al. (2009) describe the "cruel irony" of the perverse relationship between energy prices, increased fertilizer and transport costs, and the stimulation of biofuel production, with knock-on poverty and food security implications. Although the as-of-yet limited attention to the relationships between food security and rising energy prices has focused primarily on food production from agricultural systems (Pelletier et al., 2011), seafood production is similarly dependent on fossil fuels.

Nearly half of the world's population derive almost 20% of their protein intake from fish (including aquaculture) resources (FAO, 2012). In low-income food deficit countries, fish accounts for 24% of animal protein intake (FAO, 2012) and 400 million poor people are critically dependent on fish for food (FAO, 2009). Employment in fisheries continues to grow faster than in agriculture, providing direct jobs to an estimated 54.8 million people – mostly in developing countries (Teh and Sumaila, 2011). A large fraction of these are fishers engaged in small-scale fisheries. More broadly, employment associated with fish resource supply chains supports the livelihoods of roughly 10–12% of the global population (FAO, 2012). Clearly, fisheries and aquaculture make vital contributions to food security – both as a direct source of protein, micronutrients and essential fatty acids, and indirectly via employment income for food purchases (Kawarazuka and Bene, 2010; Smith et al., 2010; Garcia and Rosenberg, 2010; Srinivasan et al., 2010). However, the links between fish resource availability and affordability, energy price increases/volatility, and food security outcomes remain an under-considered issue.

Relationships between the energy intensity of food systems and food security outcomes are complex, and vary according to food production technology, geography and socio-economic context (Pelletier et al., 2011). In light of the considerable diversity of fisheries and aquaculture production systems and supply chains, and the varied socio-economic status of producers and consumers of fish products, it can be anticipated that food security outcomes associated with energy price volatility and increases will be similarly variable – as will the capacity to adapt. Here, we evaluate key vulnerabilities of fisheries and aquaculture and, ultimately, those dependent on fish resource supply chains, to energy price volatility and increases with respect to food security outcomes, and highlight opportunities and constraints to supply-side mitigation strategies for fish resource producers.

2. Methods

2.1. Characterizing the energy intensity and distribution of energy use in fish resource supply chains

We begin with a review of factors which determine the energy intensity of fish resource production, processing, and distribution systems, taking into consideration both direct and indirect energy inputs (Section 3.1). We examine major categories of fisheries and aquaculture production in turn in order to elucidate the key drivers of energy use, the extent to which different production systems may be exposed to energy price changes, and where food security impacts may potentially arise. Given that the energy costs of fish products at the storage, retail, consumption and disposal stages are likely similar to those of competing animal protein sources, we focus here on primarily production-related variables.

2.2. Characterizing country-level food security vulnerability at the fisheries viability/fish resource availability/energy price nexus

We subsequently take a global view to classify the vulnerability of countries to fisheries-related food security risks associated with energy price increases in terms of exposure (E) to energy price variations; sensitivity (S), or dependence, of the national economy upon social and economic returns from the fisheries sector; and the extent to which national adaptive capacity (AC) can offset the impact of energy price changes (Section 3.2). Here, we adapted the methods of Allison et al. (2009), which were originally developed to evaluate fisheries vulnerability to climate change. It should be noted that the choice of measures for exposure, sensitivity and adaptive capacity in such an analysis must take into account the scale of the analysis, the sector under consideration and data availability, and is hence somewhat subjective (Allison et al., 2009; Turner et al., 2003). Our selected measures for each of the three components of vulnerability are described below. The variables considered and supporting data sources are summarized in Table 1.

Exposure to energy price change was quantified based on three variables: the national price of fuel; reliance on fuel (i.e. the proportion of the national fleet that is motorized versus non-motorized); and country-specific energy intensities of fish consumption. National energy intensities of fish consumption were calculated as normalized scores out of 1, taking into account country-specific seafood consumption patterns and average energy intensities for seafood categories (e.g. crustaceans, molluscs, pelagic fish, demersal fish).

Sensitivity was calculated using three indices: an index of employment and economic dependence on the fisheries sector; an index of nutritional dependence; and affordability. The fisheries dependence of national economies was represented using a composite index which included fisheries landings, exports and gross revenues, and the contribution of fishing and aquaculture to employment. Nutritional dependence was calculated based on the contribution of fish protein to total dietary protein. Affordability was calculated based on the national food security rating and the household expenditure on food (as proxies for affordability of seafood products for the local population). We assumed that higher landings, exports, gross revenues from fisheries, contribution to employment, dietary protein and household expenditure on food implied a high dependence of the economy on the fisheries sectors and hence a high sensitivity to fluctuations in energy prices in the fisheries sector.

Adaptive capacity (national) was calculated as a composite of five variables: the size of the economy; education; income equality; financial support (subsidies) to the fishery sector; and investment in research and development (R&D) for the agricultural and fisheries sector. These variables were chosen based on the assumption that countries with high levels of economic and human development have the resources and institutions necessary to undertake planned adaptation (Allison et al., 2009).

Full datasets were available for 62 countries. Variables were standardized to obtain a mean of 0 and a standard deviation of 1. The exposure (E), sensitivity (S) and adaptive capacity (AC) indices were calculated as the unweighted sum of the standardized variables, with larger values representing higher levels for a given index.

Table 1
Summary of variables and data sources used to calculate exposure, sensitivity and adaptive capacity of nations to food security vulnerabilities associated with changes in energy prices.

Component	Interpretation	Variable	References
Exposure	Gross indicator of fuel price	Fuel price in $US/liter	Wikipedia (2013)
	Reliance on fuel	Proportion of non-motorized fleets for year 2008	FAO (2012)
		Fuel use intensity of fisheries as a score out of 1	Tyedmers (2001), Schau et al. (2009), Parker (2012) and FAOSTAT (2009)
Sensitivity (as fisheries dependence)	Index of employment and economic dependence on the fisheries sector	Fisheries export as a % of total export value for the year 2009	FAO (2013a)
		Fisheries gross revenue as a % GDP for specific year between 1996–2008	FAO (2013a) and World Bank (2013)
		Landings in tonnes per capita for the year 2009	FAO (2013a) and World Bank (2013)
		Fisheries employment as a % of total labor for specific years between 1995 and 2009	World Bank (2013) and FAO (2013a)
	Index of nutritional dependence	Fish protein as proportion of protein consumption (% g person^{-1} day^{-1}) for the year 2009	FAOSTAT (2009)
	Affordability	Household expenditure on food as a % of total household expenditure	EIU (2012)
		Food security rating as a score out of 100	EIU (2012)
Adaptive capacity	Size of economy	GDP per capita in PPP terms (international 2005 $US), average 2006–2011	World Bank (2011)
	Equality of income	GINI coefficient out of 100	World Bank (2013)
	Education	Human Development Index (HDI), average 2006–2011	UNDP (2011)
	Financial support	Fisheries subsidies for the year 2005 as a % of the gross value of landings in $US	FAO (2013a) and Sumaila et al. (2008, 2010b)
	Fisheries innovation and technology	Expenditure on Agricultural R&D as a % of the GDP	EIU (2012)

We subsequently calculated an overall vulnerability index (treating the three components equally) as $V = f(E, S, \mathrm{AC})$, following Allison et al. (2009), resulting in an unweighted mean value for each country. Final vulnerability scores were lowest (negative) for the most vulnerable countries (i.e. high exposure, high sensitivity, low adaptive capacity). For presentation, final indicator scores were categorized into 'high', 'moderate', 'low' and 'very low' vulnerability quartiles. On this basis, we identify and characterize those populations that may be disproportionately vulnerable to food security impacts associated with energy price volatility and/or increases.

2.3. Adaptive capacity of individual fishers and farmers

Focusing on supply-side mitigation options, we then describe factors that may influence the potential capacity of individual fisheries and aquaculture businesses to adapt to energy price changes (Section 3.3). We consider both technological and behavioral adaptation strategies, as well as factors that determine individual uptake capacity. This includes financial capacity, operation type and structure, individual characteristics, and governance variables.

We conclude by highlighting food security vulnerability hotspots, and both opportunities and constraints to achieving food security objectives.

3. Results and discussion

3.1. Energy intensity and distribution of energy use in fish resource supply chains

Food prices fluctuate with global energy prices (FAO, 2011a). However, the energy intensity of fisheries and aquaculture products, and the distribution of energy use along their associated supply chains, is highly variable (Fig. 1). On this basis it can be anticipated that the economic viability of these production systems and the availability/affordability of their products will be impacted to varying degrees by changing energy prices. Understanding the distribution of energy use in fish commodity supply chains – in particular, for production and processing phases – is thus essential to both understanding related food security risks and identifying mitigation options.

Energy use in fisheries and aquaculture production can be divided into two categories: Direct energy consumption, including fuel inputs to fishing vessels or aquaculture facilities; and indirect energy inputs, which encompasses all "upstream" life cycle energy consumed in the provision of inputs to these systems.

3.1.1. Fisheries

Fishing is unique among the dominant means of food production in that direct energy inputs typically comprise the largest share (75–85%) of total energy use (Tyedmers, 2004). The principle driver of energy use in fishing operations is the burning of fuel for propulsion and gear operation (Thomas et al., 2009). Indirect energy inputs to construct and maintain industrial fishing vessels and gear typically contributes, on average, an additional 10% (Smil, 2008) although, in some fisheries, the provision of bait, ice, or other forms of refrigeration may account for up to 40% of energy inputs (Tyedmers, 2004; Danish Technological Institute, 2011).

Globally, fuel inputs to fishing fleets averaged 620 liters per tonne (L/t) of fish landed in 2000 (Tyedmers et al., 2005), and 670 L/t for EU fleets (Cheliari et al., 2013). Due to the diversity of fishing strategies, which span artisanal vessels using winds, tides and oars for propulsion to fuel-powered ships equipped with sophisticated technologies, heterogeneity in energy use between fisheries is similarly marked. For fuel-powered vessels, extremes of 20–4000 L/t have been reported (Tyedmers et al., 2005; Cheilari et al., 2013).

The factors influencing fisheries energy use include gear type, vessel design and condition, species type and abundance, distance to fishing grounds, steaming speed, and management regime. In general, fisheries for small pelagics tend to be most energy efficient (20–150 L/t), whereas fisheries targeting invertebrates are typically least efficient (100–6000 L/t). Between these extremes are demersal fisheries (100–2000 L/t) and fisheries for large pelagics (500–3000 Lt/) (Thrane, 2004; Tyedmers et al., 2005; Cheilari et al., 2013).

The cost of fuel in relation to total fishing expenses varies between fisheries as well as between regions. Fuel costs tend to be

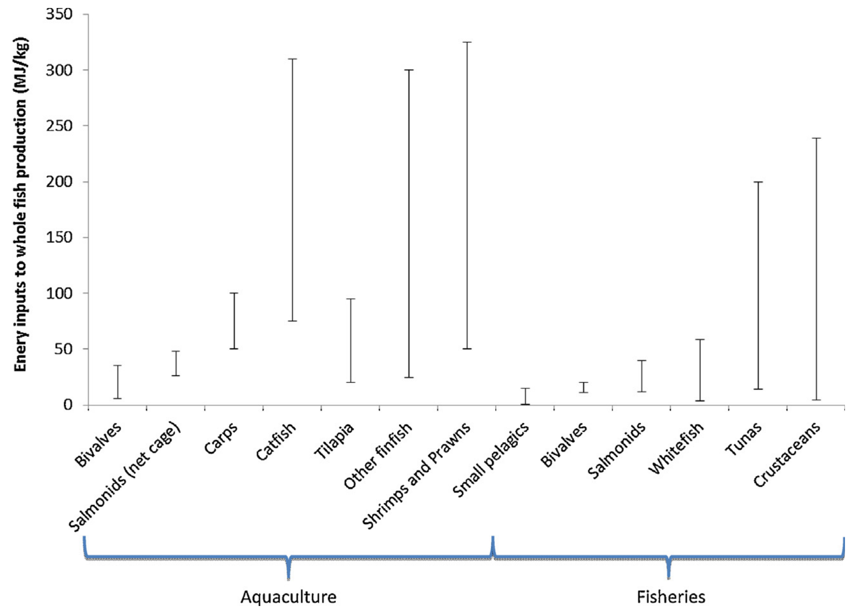

Fig. 1. Reported range of energy inputs to live-weight production of seafood from fisheries and aquaculture.
Data from Tyedmers (2001), Tyedmers (2004), Schau et al. (2009), Pelletier et al. (2009), Hall et al. (2011) and Parker (2012).

greater for vessels employing active gears, as has been observed in the case of trawlers in Australia (Thomas et al., 2009; Wakeford, 2010; Thomas and Frost, 2012) and Europe, where costs of fuel inputs to trawling vessels can exceed 50% of total expenses (SCEGA, 2008; Cheilari et al., 2013). Lam et al. (2011) constructed a database of fishing costs by country, and found that fuel accounts for a greater share of total costs for fishermen in Africa and Southeast Asia than for those fishing in Europe or Oceania. This pattern was also observed by the FAO (2007), which found that fuel costs accounted for a considerably higher share in fisheries in developing countries than their counterparts in developed countries (Fig. 2).

3.1.1.1. Artisanal and small-scale fisheries. Artisanal or small-scale fisheries commonly provide the most affordable sources of animal protein for many people in developing countries, and are also a major source of employment in coastal communities, both in the form of fishing and processing/distribution activities (Kawarazuka and Bene, 2010; Teh and Sumaila, 2011). Forty percent of the global fishing fleet is currently non-motorized, artisanal vessels (FAO, 2012). The eight least motorized fleets, by number of vessels, are all in African countries, specifically Madagascar (almost 100%), Mozambique (97%), Sierra Leone (90%), Egypt (86%), Tanzania (82%), Kenya (78%), Ghana (77%) and Uganda (73%). In such contexts, fisheries-related food security risks associated with energy price increases or volatility are low.

However, of the 50% of total global fisheries landings produced by small-scale fishers employing small vessels, two-thirds come from fuel-powered vessels (FAO, 2010). Due to the use of old and inefficient engines in many small-scale fisheries, fuel intensity tends to be higher. Old and/or poorly maintained engines may consume 30% more fuel compared to new engines (Curtis et al., 2006). This contrasts with certain developed country contexts (for example, Australia and Canada) where research-based guidelines

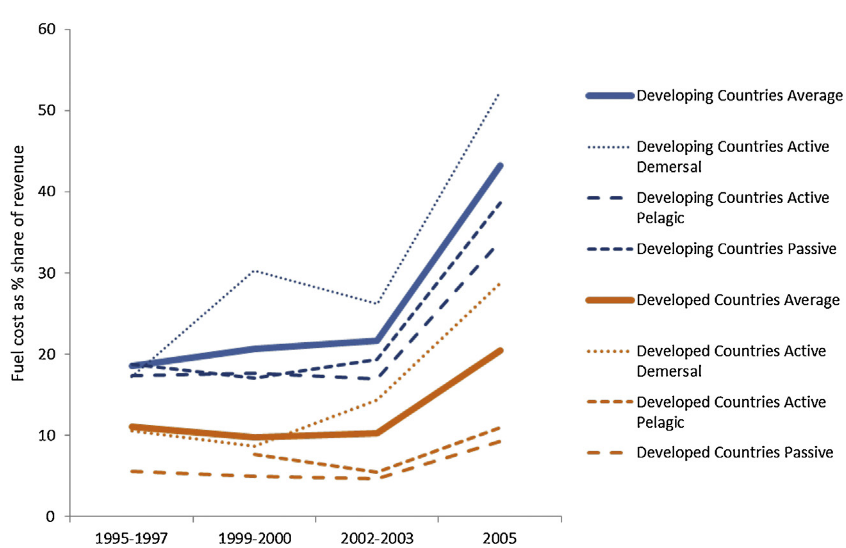

Fig. 2. Fuel costs as a percentage of revenue from fish landed in developed versus developing countries, 1995–2005
Data from FAO (2007).

for fuel efficiency have been developed and implemented (Wilson, 1999; Sterling and Goldsworthy, 2007; NFLD, 2012). Accordingly, fuel use typically comprises a greater share of operating costs in developing countries – in particular, in small vessel fisheries – although differences in wage costs, which are higher in developed countries (Lam et al., 2011), also influence this relationship.

FAO (2007) reported an average fuel cost share as a percentage of revenue of 43% (range of 34–52%) for developing country fisheries versus 20% (range of 9–29%) for developed countries. Moreover, fuel cost share appears to be increasing across fisheries over time (Fig. 2). Countries with a large fraction of small-scale, motorized vessels include Sri Lanka, and Antigua and Barbuda. In these contexts, fisheries food security risks related to energy price increases may be high for artisanal/small scale fisheries, particularly for active, demersal fisheries. Risks may also vary within, as well as between countries. For example, in Cambodia, the low-volume marine fisheries sector comprises a large fraction of small motorized vessels, whereas the much larger volume inland fisheries sector is largely reliant on passive traps and/or non-motorized vessels (FAO, 2011b).

3.1.1.2. Low-input, high-volume, low-value fisheries. Fisheries for small pelagic species, or forage fish, make up the largest sector of the global fishing industry by landings. Six of the ten highest volume fisheries in 2008 targeted small pelagics (FAO, 2010). Excluding artisanal fisheries (of which many also target small pelagic species), these fisheries typically require very low fuel inputs per unit harvest. Estimates of fuel inputs vary in the range of 20–126 L/t for purse seine vessels and 81–112 L/t for trawlers for small pelagic fisheries in the North Atlantic (Tyedmers, 2001), 79 L/t for selected EU pelagic trawlers (Cheilari et al., 2013), 106 L/t for small pelagic fisheries in Norway (Schau et al., 2009), and 16 L/t for Peruvian anchoveta, the largest pelagic fishery globally (Avadi and Freon, forthcoming). These estimates place small pelagic fisheries well below the estimated global average of 620 L/t (Tyedmers et al., 2005).

Only a small fraction of global production of small pelagics is currently used for human consumption, with the balance rendered into fish meals and oils for animal feeds and other purposes (Naylor et al., 2000; Tacon and Metian, 2009). Nonetheless, the low cost of catching small pelagic fish makes these fisheries critical sources of affordable animal protein in many low-income nations, with numerous countries importing small pelagic products to satisfy their protein deficits (Alder et al., 2008). Nigeria, the Russian Federation, Ghana, the Netherlands, and Korea import the largest volumes of pelagic fish for human consumption (Tacon and Metian, 2009). Africa has the highest per capita consumption, and Southeast Asia also evinces a strong dependence of both rural and urban populations on small pelagic fishes (Alder and Pauly, 2006). Where fuel comprises a large share of operating costs, fuel price increases may potentially undermine food security in these regions. Increasing energy prices may also indirectly impact these same populations if demands for fish meals/oils by the aquaculture/livestock industries increase in response to energy-related price differentials between substitutable feed protein sources.

3.1.1.3. High-input, high-value commercial fisheries. Among the most fuel-intensive fisheries in the world are those targeting various species of lobster with trawls or traps, shrimps and prawns with trawls, and tunas with long line (Boyd, 2008; Ziegler and Valentinsson, 2008; Schau et al., 2009; Tyedmers and Parker, 2012). These fisheries produce products of relatively high value, and are hence able to sustain high input costs. However, their high rates of fuel use make them susceptible to rapid increases in energy prices if product prices do not quickly adjust.

Individuals and groups dependent on these fisheries are likely to be disproportionately affected by increased energy prices. This includes both consumers of their products, typically in developed countries, as well as countries which benefit financially from these fisheries through employment, exports and access fees. As products from these fisheries are often considered luxury items, food security impacts associated with increased energy costs are more likely to come in the form of decreased employment and national income.

Many of the same nations that rely heavily on artisanal and small scale fisheries as a food source also have foreign-owned commercial vessels fishing marine species in their waters. While these vessels typically employ few people, they contribute to the national Gross Domestic Product (GDP) through exports as well as taxes, access fees, and levies. Of the above artisanal-dominated countries, four (Madagascar, Mozambique, Sierra Leone and Ghana) have substantial export-oriented industries characterized by foreign-owned vessels targeting shrimp by trawl and/or tuna species by purse seine or long line. In some cases (e.g. Madagascar, Ghana), foreign-owned industrial vessels are essential sources of fisheries-related GDP contributions to developing countries. Products from these fisheries are highly valued and are typically exported to the European Union or other markets in developed countries. In other cases, income from foreign-owned fisheries in developing nations comes in the form of access fees. Access fees from tuna purse seine and long line vessels account for a substantial portion of the GDP, for example, of Kiribati (Barclay and Cartwright, 2007).

In developed country contexts, while many fisheries may be vulnerable to fuel price increases/volatility, associated food security risks are likely low given the existence of social safety nets, and ease of protein substitution among affluent consumers. A recent analysis of the economic performance of more than 50 EU fleets between 2002 and 2008 showed that a doubling in fuel costs over this interval has increased average fish price by 50% and the fuel cost share of total costs from 17% up to 29%. As a result, fleet fishing activity has waned, with overall fishing effort declining 25% and landings 30% (Cheilari et al., 2013). The Italian beam trawl fleet provides a very good example. Since 2004, the fleet has reduced fishing effort by 50%, with employment in this fishery following an analogous trend.

3.1.2. Aquaculture

Aquaculture is similarly highly diverse, with more than 600 species cultured using a variety of technologies in marine, brackish and freshwater environments worldwide (Troell et al., 2004; Pelletier and Tyedmers, 2008; Pelletier et al., 2011). In contrast to fisheries, however, the ratio of direct to indirect energy inputs is not as amenable to generalization. A large share of global aquaculture production – such as the production of aquatic plants and bivalves – typically requires very little industrial energy input. At the other end of the spectrum, intensive production of crustaceans and finfish often requires considerable direct and indirect energy inputs (Troell et al., 2004).

A recent study of the biophysical impacts of global aquaculture production (Hall et al., 2011) characterized average energy inputs by species group and production environment (see Fig. 2). From this assessment and similar, more detailed studies of individual systems (Pelletier and Tyedmers, 2007, 2008, 2010; Aubin et al., 2009; Ayer and Tyedmers, 2009; Pelletier et al., 2009), it is evident that the energy intensity of aquaculture production strongly hinges on two factors: direct energy inputs to maintain water quality at the farm-level, and indirect energy inputs linked to the provision of the imported feeds consumed in fed aquaculture production.

With respect to direct energy inputs, variables including stocking density, water quality requirements of the culture organism, and culture environment are determining. Intensive, land-based flow-through or recirculation systems are often characterized by substantial energy inputs for activities such as pumping, filtering, and aerating water, as well as for lighting and feed delivery infrastructure. In contrast, direct energy inputs may be low where water quality requirements are low or where passive water exchange is provided by the host water body (for example, in net-cage systems) (Troell et al., 2004; Aubin et al., 2009; Ayer and Tyedmers, 2009; Pelletier and Tyedmers, 2010; Henriksson et al., 2012).

Production of feed, accounting for as much as 90% of cradle-to-farm gate energy demand in some intensive fed aquaculture systems (Pelletier et al., 2009; Pelletier and Tyedmers, 2010), is often the largest contributor to overall energy use. However, the embodied energy of aquafeed inputs varies widely across materials of fisheries, agricultural and livestock origin. In general, lower trophic level and less processed feed inputs will have lower associated energy demands, hence nutritional requirements of culture organisms is important. Feed conversion efficiency, both between species and within species on different diets, is similarly critical (Pelletier and Tyedmers, 2010).

Between 1980 and 2010, the proportion of fed vs. non-fed fish production from aquaculture increased from 33% to 50% (FAO, 2012). This trend is anticipated to continue. Along with a continuing transition toward high-density, high-input production technologies, this suggests an increasing vulnerability of aquaculture production to energy price increases and/or volatility – particularly in Asia, where the bulk of global aquaculture occurs. At the same time, a relative reduction of some energy-intensive feed inputs, in particular fish meal and fish oil, has been observed over time in the production of carnivorous aquacultured species (Tacon and Metian, 2008). Increasing prices for energy may spur further developments to reduce energy-intensive inputs.

3.1.3. Processing and distribution

Processing and distribution may also contribute substantially to the energy intensity of fisheries and aquaculture products (Tlusty and Lagueux, 2009; Iribarren et al., 2010). Considerable energy may be required in warehouses and dispatch centers for cooling and aeration (Iribarren et al., 2010) Product form, which is often determining for transport mode, is similarly an important variable. Frozen products moved via container shipping will have less embodied energy demands than will products moved by truck or air. For the latter, transport-related energy requirements will dominate overall supply chain energy use. For example, Australian rock lobster are airfreighted live to China, with this stage of the supply chain accounting for 54% of the carbon footprint due to the energy intensity of air freight (Farmery et al., 2013). Seafood is unique among animal protein sources in terms of the higher proportion of air freighted fresh product. Over 5% of global fisheries catches are air freighted (FAO, 2013b).

3.2. Characterizing country-level food security vulnerability at the fisheries viability/fish resource availability/energy price nexus

In light of the considerable variability in the energy intensity of fish resource supply chains and the socio-economic status of producers and consumers of fish resources, we undertook a country-level assessment of food security vulnerability at the fisheries viability/fish resource availability/energy price nexus in order to provide a broad overview of current vulnerability patterns.

We found that vulnerability to fisheries-related food security risks as result of energy price increases closely parallels the development status of nation states (Fig. 3). Developing countries in Asia, Africa and Latin America appear to be most vulnerable, whereas the most developed countries are generally least so (Fig. 3). Vulnerability is most strongly correlated with sensitivity ($r^2 = 0.76$), followed by adaptive capacity ($r^2 = 0.54$). The relationship between exposure and vulnerability is relatively weak ($r^2 = 0.12$) (Table 2). Five of the ten countries identified as most vulnerable also figure among the ten most sensitive countries. These include Cambodia and Vietnam, which rank first and second, respectively, in both sensitivity and overall vulnerability (Fig. 3). The two strongest predictors of the vulnerability of nation states to food security risks at the energy price increase/fisheries viability/fish resource availability nexus are the Human Development Index (HDI) ($r^2 = 0.48$) and food security scores ($r^2 = 0.47$), followed by household expenditure on food ($r^2 = 0.46$) and contribution of fisheries to GDP ($r^2 = 0.41$, Table 2). In other words, countries

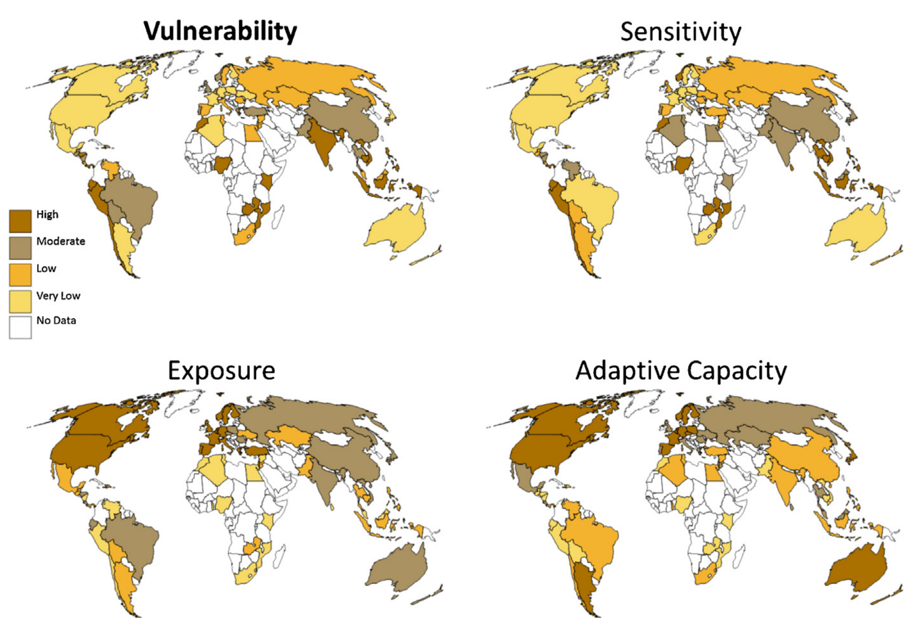

Fig. 3. Sensitivity, exposure, adaptive capacity, and overall vulnerability of 62 nation states to fisheries-related food security risks associated with energy price increases, reported in quartiles.

Table 2
Coefficient of determination for individual indicators in predicting overall country vulnerability to food security risks at the energy price increase/fisheries viability/fish resource availability nexus.

Indicator	r^2 value
Exposure	0.12
Fuel price	0.12
Fleet motorization	0.15
Fuel use intensity	0.00
Sensitivity	0.76
Fisheries exports	0.17
Fisheries GDP	0.41
Fisheries landings	0.02
Fisheries employment	0.40
Fish as % protein	0.02
Adaptive capacity	0.54
Food security	0.47
Food expenditures	0.46
GDP per capita	0.36
HDI	0.48
Fuel subsidies	0.09
R&D	0.38
GINI	0.15

which are least developed, least food secure, and which rely most heavily on fisheries as a source of food and income are most likely to suffer increased food security risks as a result of increasing energy prices. For a summary of country performance for all variables considered, see the Supporting Information file.

Norway and the UK were exceptions to this general trend in that both countries, although highly developed and food secure, appear to be moderately vulnerable to energy price increases. Like most developed countries, exposure to energy price increases is high due to relatively high fuel prices and a large proportion of motorized vessels in the national fishing fleet. Norway's sensitivity, however, is influenced by a relatively high dependence on fish as a source of food and revenue, whereas the UK's is largely determined by lower adaptive capacity compared to other developed countries. The UK does not have fuel subsidies (Sumaila et al., 2008) and the buffer to energy price changes they provide, nor is it clear whether their introduction would be politically feasible.

Among developing countries, in contrast, Argentina, Mexico and Algeria evince low vulnerability to fisheries-related food security risks associated with energy price increases. Here, low sensitivity largely reflects low dietary and economic reliance on seafood. Exposure for these countries is also low, but is influenced by different factors: low fuel prices in Mexico; low fuel usage of fisheries in Argentina compared to other countries with a similar percentage of motorized fleet such as Australia; and a combination of low fuel prices and high proportion of artisanal fisheries with low fuel intensity usage for Algeria. Adaptive capacity also varies between these three countries. In Argentina and Mexico high adaptive capacity is largely the result of fuel subsidies. Algeria, on the other hand, has a very low adaptive capacity that is nonetheless offset by its very low exposure (the lowest of all countries assessed) due to the small proportion of motorization in the fishing fleet along with very low fuel prices (albeit a lack of fuel subsidies) (Sumaila et al., 2008).

In general, Asian countries are particularly vulnerable due to a combination of high dependence on fisheries, high sensitivity and low adaptive capacity, although there is considerable inter-country variation. For example, India ranks as highly vulnerable whereas China appears to be only moderately so. The deciding difference here lies in their respective adaptive capacity. Specifically, China scores better as a result of higher GDP per capita, HDI and investment in fisheries R&D compared to India.

In Latin America, Chile, Peru, Ecuador, Panama and Honduras are seemingly highly vulnerable. All evince a similar pattern of relatively low exposure to fuel price variations due to low fuel prices, but high sensitivity linked to their dependence on fisheries as a source of income and food, very low adaptive capacities due to low GDP per capita, a lack of fuel subsidies, and low levels of investment in fisheries R&D.

While complete datasets were not available for many African nations, the vulnerability of countries that we were able to assess was mixed, ranging from high (e.g. Zambia) to very low (e.g. Algeria). One common characteristic, however, was the low to very low exposure of African countries as a result of (a) high levels of non-motorized artisanal fishing and (b) consumption of small pelagic fish from fuel-efficient fisheries.

Interestingly, we observed a relatively consistent relationship between exposure to energy price increases and adaptive capacity. In general, the world's richest nations are more exposed to increased energy prices due to highly motorized fishing fleets and seafood diets that include a higher proportion of energy-intensive species such as crustaceans. However, this is countervailed by high incomes and high fisheries subsidies. As a result, most developed nations rank among the most able to adapt. It should be noted that, although we count fisheries subsidies as contributing positively to the adaptive capacity of nations to energy price increases, they are generally considered undesirable as a fisheries management strategy (Sumaila et al., 2010b). In many regions with ineffective fisheries management the long-term economic impact of subsidies is negative, as they are thought to promote overfishing, decreased catch per unit effort, decreased biomass, and reduced profitability (Sumaila et al., 2010a; Heyman et al., 2011).

3.3. Adaptive capacity of fishers and aquaculture farmers

As a result of current energy price increase trends, and the likelihood of further volatility, context-specific adaptation strategies will be required in order to both ensure the viability of fishing and aquaculture operations as well as continued affordable supply of fish resources to consumers – in particular, those most vulnerable to food security impacts. While adaptive capacity (as influenced by the size of the economy; education; income equality; financial support to the fishery sector; and investment in research and development (R&D) for the agricultural and fisheries sector) was considered at the national level in Section 3.2, the capacity of individual fishers and aquaculture producers to adapt to energy price change (i.e. supply-side mitigation) is the focus of this section. Here, adaptive capacity is defined as "the degree to which adjustments in practices, processes, or structures can moderate or offset the potential for damage or take advantage of opportunities created by a given change" (IPCC, 2001). Since the energy intensity of fish resource supply chains is typically disproportionately determined at the production stage (except in the case of air-freighted seafood products), we restrict our analysis to production-level considerations.

3.3.1. Adaptation options

Fishers and aquaculture farmers (herein called 'farmers') may leverage a variety of opportunities to adapt to increases in energy prices and energy price volatility. The most obvious option for any operation, regardless of fishery or farm type, is to make structural adjustments where possible in order to reduce reliance on expensive, direct energy sources such as fuel. Fisheries, for example, could invest in newer, more efficient vessels (Abernethy et al., 2010), modify hull design, change engine type (e.g. using hybrid propulsion such as diesel + electric + battery), replace diesel with alternatives such as electricity, natural gas, or bio-diesel (although this is currently more expensive), and integrate alternative power sources on board (e.g. auxiliary power) (European Commission Directorate-General for Fisheries and

Maritime Affairs, 2006; Stouten et al., 2007). Energy use reductions during fishing operations could also be achieved with improvement of fishing gear technology, including gear design and net construction in order to reduce towing drag and resistance of nets (for example, by using smaller diameter twines or lighter materials). Aquaculture farms could reduce reliance on energy-intensive fish and other animal input based feeds, and experiment with mariculture, flow-through rearing environments (De Young et al., 2012) and other systems where ecosystem services maintain water quality in place of fossil energy-intensive processes. Lowering stocking densities in ponds may also decrease energy costs of aeration and pumping, but with trade-offs in terms of potential productivity. Most of these options, however, require significant investment and hence are limited to those operators that can afford such changes.

Behavioral change at the level of individual operators may also reduce energy use or reliance on expensive energy sources. For instance, reducing cruising speed can significantly reduce fuel consumption within fisheries, although it comes at the cost of increased steaming time and hence reduced time for fishing (European Commission Directorate-General for Fisheries and Maritime Affairs, 2006; Abernethy et al., 2010). Fishers could also adjust where and when they choose to fish. For example, in an attempt to increase fuel efficiency in the face of increasing fuel prices, many operators in the UK's southwest fishing fleet fished closer to port, fished with the flow of the tide rather than against it, and fished in clement weather only. They also traveled more slowly when fishing or steaming. Each of these options reduced fuel use; however, they generally came at the cost of reduced catches, with knock-on consequences for seafood availability (Abernethy et al., 2010). Dutch beam trawler skippers similarly changed their fishing behavior to reduce energy costs by substantially reducing towing speed (Beare and Machiels, 2012). In the salmon aquaculture industry, automated feeding systems have helped to improve economic feed conversion ratios (due to lower feed loss), effectively trading off higher on-farm energy inputs associated with automated systems for reduced indirect energy consumption related to feed input supply chains.

In some instances, fishers could also transition to less energy-intensive fishing methods (Stouten et al., 2007). Driscoll and Tyedmers (2010) underscored the advantage of banning midwater trawling in the New England Atlantic herring fishery, which resulted in the re-emergence of the fixed gear fishery and inadvertently reduced fuel intensity. Stouten et al. (2007) also suggest that European fisheries will shift away from large beam trawlers toward smaller shrimp trawlers and more passive fishing techniques (although the authors state this would result from some fishers exiting and new fishers entering the fleet, rather than individuals making the change themselves).

3.3.2. Capacity to uptake adaptation options

Change is an integral part of fisheries and aquaculture, and businesses are continuously adapting to change (De Young et al., 2012; Rossiter, 2006). Arnason (2007: cited by Stouten et al., 2007) suggests initial impacts of fuel price increases will make businesses less profitable, but the initial impact will soon be counteracted with effective adaptive strategies. However, similar to the magnitude of energy costs, the capacity of individuals and businesses to adapt to change will be highly variable. Adaptive capacity within fisheries and aquaculture is currently most commonly explored in relation to climate change (e.g., see Adger et al., 2005; Smit and Wandel, 2006; Daw et al., 2009; Badjeck et al., 2010; Marshall, 2010); nonetheless there are many findings of relevance to any change.

Capacity to adapt to change depends on variables such as financial capacity, operation type and structure, and individuals' inherent adaptive capacity in terms of their ability to cope with, learn from and manage risk and change (Marshall and Marshall, 2007; De Young et al., 2012). Governance also plays a critical role in determining whether adaptation options are limited or available (Armitage, 2005). While many of these features vary between developing and developed nations, they are equally applicable to both.

3.3.2.1. Financial capacity. Financial capacity is likely the critical element affecting whether most fishers or farmers can take advantage of adaptation options. For individual operators, financial capacity relates to income and livelihoods, business size, and the existence of a financial buffer. Many artisanal fishers and farmers in developing countries, for instance, have limited financial capacity to implement change within their business, even if those changes result in long-term savings (Cinner et al., 2009). Those business owners with diverse livelihoods have greater capacity to adapt to change (Marschke and Berkes, 2006; Cinner et al., 2009; De Young et al., 2012); however, their adaptation may remove them from the fishery/farm (Cinner and Bodin, 2010), which may affect access to seafood at the household and, potentially, local market level within communities. Larger businesses with high incomes tend to have a larger buffer to absorb the costs of change, can take bigger risks, and experiment with their available options (de Sherbinin et al., 2008; Marshall, 2008). Generally, larger businesses are more likely to buffer themselves from unpredictable problems (Fisher, 2001). However, large businesses are sometimes limited by the level of investment they have made in their current structure. For example, in the case of the Coral Reef Finfish Fishery operating within Australia's Great Barrier Reef, larger businesses were found to be less able to adapt to temporary changes in resource abundance following an extreme weather event due to their need for continued income to meet investment costs. In this instance, while the businesses were considered 'large', they lacked the financial buffer to implement necessary changes to their operation (Tobin et al., 2010). From the perspective of financial adaptive capacity, food security risks are hence likely to be highest in relation to fish resources from artisanal fishers and farmers, and where businesses lack sufficient financial buffer to implement changes.

3.3.2.2. Operation type and structure. Operation type and structure relates in part to business size, but more to the type or method of fishing/farming, and level of specialization versus diversity of operation. Some operations will be easier to adjust than others, and will require different levels of investment to alter. For instance, while changing from mobile to fixed netting operations will reduce fuel use in the long term (Suuronen et al., 2012), it requires significant investment in new equipment, potential changes to vessel design, and retraining of crew in the short term. Diversifying to different species that require lower energy inputs to catch (due to higher abundance, for example) or culture in order to take advantage of market opportunities, however, may not require as substantial an investment if the same or similar methods can be utilized. Again, the existence of a financial buffer becomes critical here.

Diversification of operations is considered an advantage for adaptation to change for both fisheries and aquaculture (Christensen and Raakjaer, 2006; Coulthard, 2008; De Young et al., 2012). Diversification is often discussed in relation to livelihoods (e.g., see Marschke and Berkes, 2006); i.e. diversification of individual or household employment to include income external to the fishery or farm. However, it is also relevant within fishing and aquaculture. For example, when investigating adaptive capacity of fishing villages in a South Indian lagoon, Coulthard (2008) found it was not the poorest who were the least able to adapt to change, but rather fishers who had become locked into an overly specialized fishery with restricted fishing methods and species. Similarly, within Australia's Coral Reef Finfish Fishery, those businesses that were already operating with multiple gear types in multiple fisheries, and/or marketing a diversity of species, were able to take advantage of market opportunities for other species when the main harvest species became less available due to extreme weather. In contrast, highly specialized fishing businesses were unable to diversify due to lack of infrastructure, established markets, and fisher knowledge regarding how to process diverse product or operate with different gears (Tobin et al., 2010). Artisanal aquaculture may also reduce vulnerability at the farm level where it contributes to diversification of farm production. Dey et al. (2010) found that farms with artisanal aquaculture ponds fared better than those without during times of drought in Malawi. Artisanal aquaculture may contribute directly to the food security of producers or (in some cases, more commonly) indirectly via increased household income for food purchases (Kawarazuka and Bene, 2010). In general, specialization may therefore be negatively correlated with food security outcomes in face of energy price changes.

3.3.2.3. Individual adaptive capacity. Regardless of financial capacity and business structure, individuals have different levels of inherent capacity to adapt to change (Adger et al., 2005; Coulthard, 2008). In part, this depends on demographic characteristics. For example, Cinner et al. (2012) explored adaptive capacity to climate change across 29 reef-dependent communities in five western Indian Ocean countries and found not only large differences in adaptive capacity across communities, but also that vulnerability to change differed within communities according to variables such as age, gender and marginalized groups. Other important demographic characteristics included educational attainment, alternative employment experience, and family structure. For instance, older fishers/farmers, with low education, limited experience outside of fishing/aquaculture, and dependent families, were likely to be less adaptive than younger, more educated, independent operators (Marshall et al., 2007). Efforts to mitigate food security risks due to the impact of energy price changes on fish resource supply chains must therefore be attentive to these variables in order to identify and safeguard groups that are most at risk.

3.3.2.4. Governance. Governance, particularly in relation to fisheries, may enhance or inhibit the ability of individuals, sectors or communities to experiment with and adopt solutions to change – critical elements of adaptive capacity (Adger and Vincent, 2005; Berkes and Seixas, 2005; Marshall, 2010). Governance structures that are centralized, or top-down, are likely to have more negative influences on adaptive capacity compared to decentralized participatory approaches such as community-based or co-management regimes, given that inclusion of stakeholders in the management process is more likely to address both environmental and socio-economic goals (Armitage, 2005; Berkes, 2009; Fujita et al., 2010; Lane, 2011). Mahon et al. (2008) argue that fisheries need to be managed in a way that enables self-organization in order to improve adaptive capacity and resilience to change, with regulation becoming secondary rather than primary. Adaptive co-management is arising as one of the more effective ways to ensure natural resource industries are adaptive to change (Tompkins and Adger, 2004; Armitage et al., 2007; Berkes, 2009). This requires ensuring that policies are flexible and able to adjust to unforeseen changes or policy outcomes, adjusting to new information as it becomes available and allowing communities and individuals to self-organize (Grafton, 2010; Lane, 2011).

Regarding regulations, management decisions, particularly those made within top-down governance structures, typically do not consider potential impacts on fuel use (Driscoll and Tyedmers, 2010; Fujita et al., 2010). Fisheries regulations often include a combination of input controls – such as limits on vessel size, engine size, gear type, and harvest species – and output controls – such as total allowable catch quotas – in an attempt to control fishing effort and harvest for purposes of ecological sustainability (Lane, 2011). However, input controls, in particular, almost always limit economic efficiency (Branch et al., 2006), and regulations are not easily changed when required in the face of energy price increases or shocks (Lane, 2011).

A typical reaction to change in fuel price in developed countries is for governments to provide fuel subsidies to assist fishers, at least in the short term. However, fuel price increases and volatility are unlikely to be a short term problem, and subsidies that 'lock in' existing fishing or farming practices are mal-adaptive: it does not encourage adoption of adaptive strategies for long term sustainability (Sumaila et al., 2008; Grafton, 2010). Formulating policies so as to increase the resilience of fisheries and aquaculture to energy price changes should be viewed as an important component of furthering food security objectives.

4. Conclusions

Whereas previous research has variously considered the food security impacts of unsustainable harvest in fisheries, or the business impacts of increased fuel costs for fishing fleets, we demonstrate how, to what extent, and in what contexts changing energy prices may impact both producers and consumers of fish resources in terms of food security outcomes. We also highlight opportunities and constraints to adaptation on the supply-side.

Our analysis suggests that current trends of energy price increases and increased volatility exacerbate vulnerability to food security impacts at the fisheries viability/fish resource availability/energy price nexus. However, we find that vulnerability is both unequally distributed and influenced by myriad factors. Measures to mitigate food security risks in situations of high vulnerability must therefore be attentive to identifying and leveraging context-appropriate strategies. The variables described herein provide a useful starting point for characterizing and responding to food security risks in such contexts. These include considerations of fisheries viability in the face of energy price change, the impacts on availability of fish resources to dependent populations, and a spectrum of socio-economic variables that influence the adaptive capacity of fishers/farmers and/or consumer access to fish resources.

The energy intensity of fish resource supply chains spans several orders of magnitude, from negligible inputs of exogenous energy to upwards of four liters of fuel per live-weight kg of production. Determining factors of energy intensity in fisheries include gear type, vessel condition, species type and abundance, distance to fishing grounds, steaming speed, and management regime and, for aquaculture, feed and water requirements of the culture organism. The relative importance of direct versus indirect (supply chain) energy use also varies. This variability underscores that different fish resource supply chains will be impacted to different degrees by energy price change, and with varied implications for food security outcomes.

We found that country-level vulnerability to fisheries-related food security risks as a result of energy price increases closely parallels the development status of nation states, with developing countries in Asia, Africa and Latin America appearing to be most vulnerable. In particular, vulnerability is most strongly predicted by country-specific Human Development Index and food security scores, as well as household expenditure on food and contribution of fisheries to GDP. On this basis, we conclude that it is the least food secure consumers in developing countries, many of which rely heavily on fisheries as a source of food and income, that are disproportionately vulnerable to food security risks at the fisheries viability/fish resource availability/energy price nexus. These insights merit further consideration and accommodation in the context of national and international food security initiatives.

It should be noted that aggregated indices such as the vulnerability index presented here can potentially obscure important differences in how various contributing elements of an index influence final scores. Comparisons across time can also be problematic due to the "snap shot" nature of the data employed. The reader is hence invited to also consider the individual indicator scores at country-level (available as a Supplementary Information file) for more in-depth analysis of food security risks in specific countries, keeping in mind that conditions can and will continue to change over time. Nonetheless, considering a broad range of assessment criteria is essential to identifying patterns and processes that cause or increase vulnerability at the country scale, since these may differ between countries. Indeed, it is at this level that policies are formulated and implemented to secure trade, food production and food security, which must necessarily be attentive to context-specific variables. Accordingly, the index-based approach employed here can help to identify priority areas for improving adaptive capacity to stressors – in this case to fuel price shocks for fishers/farmers and the communities that depend on them – and how/why they differ between regions and sectors.

We also show that the adaptive capacity of individual fishers/farmers to energy price changes depends on both the available options for reducing direct and indirect energy dependence via technological or behavioral measures, and on context-specific uptake capacity for such measures. Uptake capacity is, in turn, influenced by financial capacity, operation type and structure, and individual characteristics as well as governance structures. In areas flagged as disproportionately vulnerable to food security impacts, policies to support supply-side mitigation strategies may be efficacious in reducing food security risks, but should be attentive to these factors.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2013.11.014.

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