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Chapter 14

MEETING SOCIOECONOMIC OBJECTIVES IN GHANA'S SARDINELLA FISHERY

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ABSTRACT

It is frequently stated that there are explicit tradeoffs between biodiversity conservation and poverty reduction. This Chapter examines these tradeoffs through the interaction between Ghana's artisanal canoe fishery and the offshore trawler fishery. Ghana's marine biodiversity is threatened by a sizeable fishing industry partly because poverty is rife, and also because the coastal population has a high dependence on fish for their food security. The artisanal fishing fleet targets small pelagics, predominantly round sardinella (*Sardinella aurita*), with their catch used mainly for subsistence. By-catch in the trawler fleet, which includes round sardinella, is mainly consumed in urban areas within the country, while their target species are exported. Current artisanal sardinella catch is insufficient to meet subsistence needs, and therefore domestic reliance on trawl-caught sardinella for food security might be in conflict with the conservation of biodiversity. We develop a bioeconomic model, which illustrates that giving priority to the effective management of the artisanal fishery in Ghana could provide food and job security to the fishers of Ghana, without compromising biodiversity conservation, in contrast to the commercial trawl fishery. It appears that the sardinella fishery may be overcapitalized, as optimization results suggest effort could be cut in half while still providing catch levels of about 300,000 tonnes per year, or four times current artisanal catches. Limiting by-catch and spatial conflicts by the trawl fishery could yield economic benefits from the artisanal sector of over US$200 million over 20 years.

1. INTRODUCTION

Biodiversity conservation in regions grappling with poverty has been widely discussed in recent years, with suggestions that poverty constrains conservation objectives (e.g., Adams et al., 2004, Sumaila, 2005). The relationships between biodiversity conservation and human well-being, however, remain poorly understood, particularly the consequences of changes in ecosystem services on the provision of food security for poverty reduction (Carpenter et al., 2006).

Loss of marine biodiversity may profoundly reduce the ocean's ability to produce seafood, filter pollutants and rebound from stresses such as overfishing (Worm et al., 2006). Despite international engagements and agreements, a policy gap exists between marine biodiversity conservation and issues such as food security (Pullin, 2004). The current Chapter addresses this gap by modelling the possible interactions between biodiversity conservation, and food and income security, using Ghana's marine fisheries as a case study. Biodiversity can be considered at three stages: genetic diversity, species diversity and ecosystem diversity (Sumaila, 2000). For the purposes of this Chapter, we consider diversity at the genetic and species level, specifically for *Sardinella aurita* (herein referred to simply as sardinella) targeted by the artisanal fishing sector in Ghana, but also related to species diversity in the Gulf of Guinea in general. We analyse two main fishing sectors: the artisanal canoe fleet and the semi-industrial trawl fleet, and in doing so, conclude that the goals of biodiversity conservation and social well-being are not always at odds.

In Ghana, high value fish are exported, with low value fish being imported, and in 2007, Ghana imported almost three times what it exported (GEPC, 2008; MRFD, 2008). This implies that domestic fisheries are not meeting domestic demand. In this analysis, we are interested in meeting domestic demand, and maximizing profit from a fishery that is both culturally and socially important, and supplies fish for the domestic market, in an effort to include social objectives. It should be noted that we are not interested in maximizing profits from exports because, while export of high value fish can bring revenues into the country, it often leaves small-scale fishers with no fish and no money accumulated from trade (see, for

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example, the social consequences of promotion of the export-driven Nile perch fishery in Lake Victoria in Baskin, 1992).

In the next section, we provide a brief description of Ghana's marine fisheries. This is followed by the development of a bioeconomic model to analyse the interaction between the artisanal canoe and semi-industrial trawl fleets. Specifically, the aim of this Chapter is to address whether or not marine biodiversity conservation need be traded-off with food security with respect to fisheries. Finally, the results from the modelling work are presented, with a discussion of the implications for (i) biodiversity conservation; (ii) the socioeconomics of Ghana's fisheries sector; and (iii) the country's plans for poverty reduction.

1.1. Ghana's Marine Fisheries

Unlike many West African nations, Ghana has a deep-rooted tradition of fishing that parallels a heavy reliance on fish for food security (Atta-Mills et al., 2004). Members of the Fanti tribe living in what is now known as Ghana were found fishing in lakes and rivers when the first European explorers arrived from Portugal in the 15th century. Ghana's marine fishery emerged during the 19th century when river canoes were modified to transport European explorers and handle the rough waves along the coastline (Agbodeka, 1992). The colonial era precipitated many changes in the traditional fishing approach (Walker, 1999), as did the political and economic changes that would follow Ghana's independence from Britain in 1957. In the decades following sovereignty, Ghana earned a reputation as one of the West African leaders in fisheries development. Both semi-industrial and industrial fleets began competing with the nation's centuries-old canoe fishery sector.

Atta-Mills et al. (2004) provide a detailed description of the history of Ghana's marine fisheries, and discuss several reasons for the recent decline in the commercial sector, which include regional political developments, globalization and the expansion of foreign fishing fleets. A decline in the commercial sector resulted in the loss of 100,000 jobs within the 4 years from 1992 to 1996 (Atta-Mills et al., 2004). Although the fisheries sector employs only 2.5% of the Ghanaian population, it actually employs about 20% of the labour force (Atta-Mills et al., 2004). Fishing is one of the most important forms of both direct and indirect employment-generating activity in Ghana's coastal area (Akpalu, 2002).

The people of Ghana, both coastal and inland, are heavily reliant on fish as a source of animal protein. The overall catch per unit effort for Ghana's fisheries has declined in recent years (Atta-Mills et al., 2004), which is cause for concern given this heavy domestic reliance on fish, and concerns of food shortages in Sub-Saharan Africa (Pinstrup-Andersen, 1999). In fact, Ghanaians derive nearly 10% of their total protein from fish (GSS, 2002), and two thirds of their animal protein (Thorpe et al., 2005), which is more than three times the world average (WRI, 2003). The majority of the population consumes fish daily, as on average, it is the cheapest animal protein available to Ghanaians (Heinbuch, 1994). However, annual demand for fish products is almost twice as high as domestic supply (WRI, 2003, Atta-Mills et al., 2004).

Ghanaian fish markets are dominated by small pelagic fish, such as sardines, anchovy and mackerel, which are caught by the canoe and the semi-industrial fleets. The availability of small pelagic fish is dependent on a seasonal upwelling, which corresponds to colder sea surface temperatures and the rainy season from June to October (Bakun, 1995; Demarq and

Aman, 2002). In good years, the artisanal fishery for small pelagic species can supply up to 70% of the landed catch (MRFD, 2007). Offshore tuna fisheries are important in the export sector. Recent government figures puts the contribution of the fisheries sector to Ghana's gross domestic product at 4.5%, and in 2007 the country earned over US$ 186 million from export of fish and fishery products (GEPC, 2008). Note, however, that the GDP figure does not capture the total value of subsistence fishing, of which the artisanal sardinella fishery is an essential part.

1.2. The Sardinella Fishery

The artisanal fishery is characterised by the use of several gears. These include purse seine nets, beach seine nets, drifting gill nets and hook and line. These gears are mainly operated from dug-out canoes made from wawa (*Triplochiton scleroxylon*) trees. There are currently about 124,000 fishers employed in the artisanal sector. This number is quite close to the 123,000 fishers reported in 2001 (Bannerman et al., 2001), so it does not look like effort, in terms of number of fishers, has moved in or out of the artisanal sector. A total of about 11,000 canoes operate actively from over 300 landing sites located along the over 500 km length of the coastline (Amador et al., 2006). Just over half of these canoes are powered by outboard motors with engine power of up to 40 hp. (Amador et al., 2006). Canoes carry crews of up to 20 people.

The target fish species for the artisanal fleet is round sardinella, although the flat sardinella, *S. maderensis*, is also caught (Bard and Koranteng, 1995) (Figure 1.). The country's Fisheries Bureau of Statistics estimates the 2006 artisanal sardinella catch to be around 87,000 tonnes (MFRD, 2007). The artisanal sector employs 80% of Ghanaian fishers. Although it is typically men out on the boats fishing, women play an important role in artisanal fisheries, being almost solely responsible for selling the fish in markets (Akrofi, 2002). An informal but strong institutional framework governs artisanal fisheries at the village level (Bennett, 2000).

1.3. The Semi-industrial Trawl Fishery

There are about 230 trawl vessels currently operating in Ghana. These vessels are multi-purpose and are used for both purse seining and bottom trawling. They operate as purse seiners during upwelling periods and switch to trawling for the rest of the year. The trawl fishery targets shrimp, seabream, barracuda and cuttlefish for export (Heinbuch, 1994) (Figure 1). The majority of trawl fishing occurs within 50 miles of Ghana's 200 mile Exclusive Economic Zone (EEZ) (Koranteng, 1997), which has led to conflicts between the artisanal canoe fleet and trawlers due to lost and damaged gear to the artisanal fishers (Marquette et al., 2002). Furthermore, there is a high proportion of by-catch fish in the trawl catch (FAO, 2004; Nunoo et al., 2009), one species of which is *Sardinella aurita*. In fact, a 1997 report suggests that as little as 4% of shrimp trawler catch is actually shrimp (Nunoo and Evans, 1997).

Trawl by-catch sometimes contributes to food security, as Nunoo et al. (2009) suggests, through the sale of fish that would otherwise be discarded. However, it seems from a biodiversity and social standpoint that it may be more optimal to have these fish captured by the artisanal fleet, and to have the trawl fisheries make a better effort to avoid by-catch. Interestingly, this sale of fish from trawlers to canoe fishermen at sea has the effect of actually keeping trawlers closer to shore (Nunoo et al., 2009), which may be undesirable from the canoe fleet's perspective, as discussed in Section 2.3.

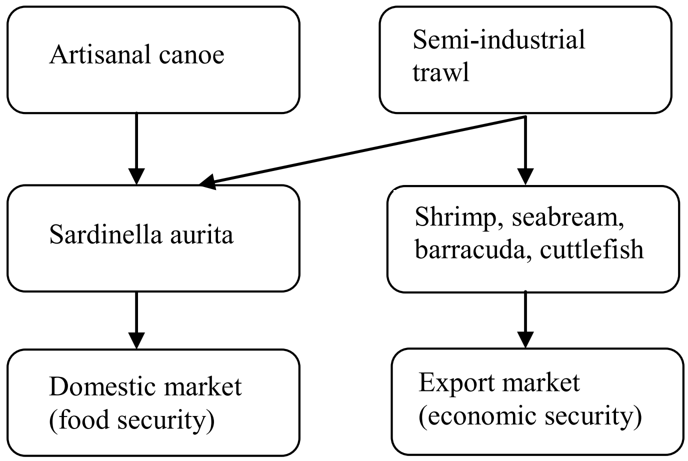

Figure 1. Fisheries sector, species caught and markets supplied.

2. THE MODEL

2.1. Biological Model

A simple Schaefer catch equation is used to simulate the artisanal catch, ($h_{a,t}$) of sardinella (Schaefer, 1957)[1]:

$$h_{a,t} = qE_tB_t \tag{1}$$

where q is the catchability coefficient of the artisanal fleet on sardinella, E_t is the artisanal effort at time t, and B_t is the biomass of sardinella at time t.

The total sardinella catch is composed not only of the artisanal catch, but also some amount of by-catch associated with other fisheries, such as the trawl fishery. This trawl by-catch is primarily sold in urban centres for domestic consumption. Total sardinella removals are calculated as:

$$h_t = h_{a,t}(1+\theta) \tag{2}$$

[1] The Schaefer catch equation, as written here, assumes a constant catchability coefficient. This assumption will be modified in a more technical version of this paper to be submitted to the primary literature. Specifically, we will allow for the schooling behaviour of sardinella to be incorporated into the catch equation in the sense of Mackinson et al. (1997).

where θ denotes by-catch as a proportion of the artisanal catch. For example, if we assume that by-catch is equal to about 5% of what the artisanal fishers catch, then θ = 0.05. This parameter will be varied in the analysis to illustrate the potential effect of by-catch on sardinella stocks and any subsequent effect on artisanal catch.

The sardinella population is modelled assuming the following simple logistic growth model:

$$B_{t+1} = B_t + gB_t\left(1 - \frac{B_t}{K}\right) - qE_tB_t(1+\theta) \tag{3}$$

where g is the intrinsic growth rate of the stock and K is the stock carrying capacity, essentially the largest stock size possible as a result of environmental limitations.

2.2. The Economic Model

Total single period revenue for the artisanal fishery is assumed to be a linear function modelled as:

$$TR_t = p_a h_{a,t} \tag{4}$$

where p_a is the ex-vessel price of artisanal-caught sardinella.

The total cost of fishing is modelled as an almost linear equation (see Flåm, 1993; Sumaila, 1995, 1997):

$$TC_t = \frac{c_a E_t^{1+b}}{1+b} \tag{5}$$

where c_a is the unit cost of effort for the artisanal fishery and b is a scalar parameter that allows concavity in the cost function and thus convergence to a solution. Unit cost is composed of both fixed and variable costs. Fixed costs include investment inputs to effort, such as purchasing gear or a vessel. Variable costs include fuel, food, labour, gear maintenance, etc. The cost of externalities, such as how the fishery may impact habitat or biodiversity, are not explicitly captured in the cost equation, as they generally do not play into decision-making by fishers.

The single period profit, or economic rent, of the artisanal fishery is the difference between the total revenue and the total cost of fishing:

$$\pi_t = TR_t - TC_t \tag{6}$$

The fisheries manager is assumed to choose a fishing effort to maximise the net present value (NPV) of the fishery, which is the discounted profit through time:

$$\max_{E} \Pi_t = \delta^t \sum_{t=1}^{T} \pi_t \tag{7}$$

where δ is the discount factor, which is equal to $1/(1+r)$, where r is the interest rate. Note that we are optimizing effort to maximise the economic rent of the artisanal fishery only as argued in the introduction. The optimisation algorithm can be found in the Appendix. Simulations were run for a 20-year time period.

2.3. Modelling By-catch and Spatial Issues

The parameter, θ, introduced earlier, models the amount of sardinella by-catch in the semi-industrial trawl fishery. Instead of explicitly modelling this fishery, for which the data requirements would be quite large, we made θ a number that would be multiplied by the total artisanal catch and would represent by-catch. Theta ranges from 0, where there is no by-catch of sardinella species in the trawl fishery, to 2, where the amount of sardinella caught as by-catch in the trawl fishery is twice the amount of artisanal catch, or two thirds the total sardinella catch. Assuming the canoe sector could totally meet domestic demand, we might reasonably strive for a by-catch-free trawl fishery. This is why our bottom range of simulation possibilities involved no by-catch. The high level of by-catch associated with some trawl fisheries, as in the shrimp fishery reported in Nunoo and Evans (1997), led us to choose a maximum of 2 for our simulations. While keeping all other parameters constant, we varied θ to estimate how the amount of by-catch could affect the catch and NPV of profit accruing to the artisanal fishery.

The majority of semi-industrial fishing occurs within 50 nautical miles of Ghana's 200 mile EEZ (Koranteng, 1997) and the competition for resources on Ghana's continental shelf has resulted in decades of conflict between the industrial and canoe sectors, including territorial disputes and destruction of gear (Marquette et al., 2002). There has been increased concern over the spatial overlap between trawlers and the artisanal canoe fleet because the trawlers have been moving closer to shore in recent years (Aman, 2007), and, to the disdain of fishermen, these conflicts have not been dealt with effectively (Lenselink, 2002).

To demonstrate this spatial interaction in a non-spatial model, we varied the cost of fishing in the artisanal sector. The present-day cost per trip for the artisanal fleet is about $169 US$ (Table 1). We decreased this by 15% and 30% to estimate how a reduction in spatial conflicts resulting in less damaged/lost gear would impact the artisanal fleet. Similarly, we increased the cost of fishing by 15% and 30% to model how an increase in spatial conflicts resulting in an increase in damaged/lost gear would affect the artisanal fleet. These simulations were first run assuming that there is no by-catch in the trawl fishery (i.e. $\theta = 0$), and then re-run assuming that the amount of by-catch is 50% and 100% of the total artisanal catch (i.e., $\theta = 0.5$, and $\theta = 1$).

2.4. Data and Input Parameters

To translate the analytical model to an empirical one, parameter values are obtained from the literature and fed into the simulation. Data for the catch and effort estimates that helped parameterise the model came from two main sources (Table 1). The biological data were taken from a *Sardinella aurita* study published by the FAO (Nansen, 2001), while the economic data were obtained from Ghana's Fisheries Bureau (MRFD, 2008).

Table 1. Model parameters, values and sources

Parameter	Symbol	Quantity	Source
Internal growth rate	r	1.42	Nansen, 2001
Carrying capacity (t)	K	1,000,000	Nansen, 2001
Catchability	q	$1.8x10^6$	Nansen, 2001
Ex-vessel price (US$/t)	p	520	Based on average prices from 1995-2006, converted to real US$ (MFRD, 2008)
Cost per trip (US$)	c	169	Based on average fixed and variable costs for canoe sector in 2007 (MFRD, 2008)

3. Simulation Results

3.1. Trawl By-catch

As described in the model section above, we varied the amount of by-catch in the trawl fishery to analyse how it may affect the sardinella fishery. The amount of sardinella caught is limited by biological constraints in the model. As such, when by-catch is relatively low (i.e., $\theta < 1.5$) it does not appear to affect the overall catch available in the system, but rather affects the amount of the biomass that is accessible to the artisanal fleet. As θ becomes greater than 1.5, we start to see the total equilibrium sardinella catch drop off. While an equilibrium catch of about 600,000 tonnes per year is possible, as by-catch increases, the catch taken by artisanal fishers decreases (Figure 2).

Because the artisanal catch decreases with increasing trawl by-catch, so does the NPV from the artisanal fishery (assuming prices and costs stay constant; the cost results are presented in the next section). Figure 3 shows the drop in NPV of the fishery. The difference between the two extreme cases, no by-catch, and by-catch equal to twice the artisanal catch, is US$ 486 million, discounted over 20 years or an average of US$ 24.3 million per year.

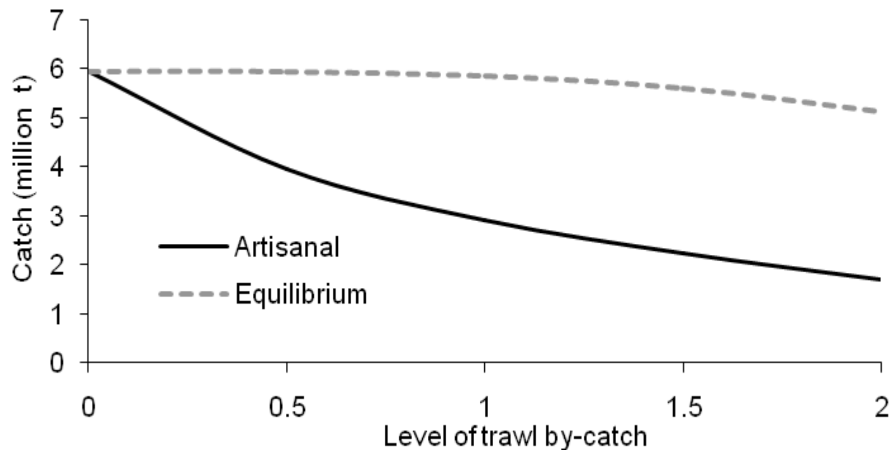

Figure 2. Equilibrium total and artisanal sardinella catch at increasing levels of trawl by-catch.

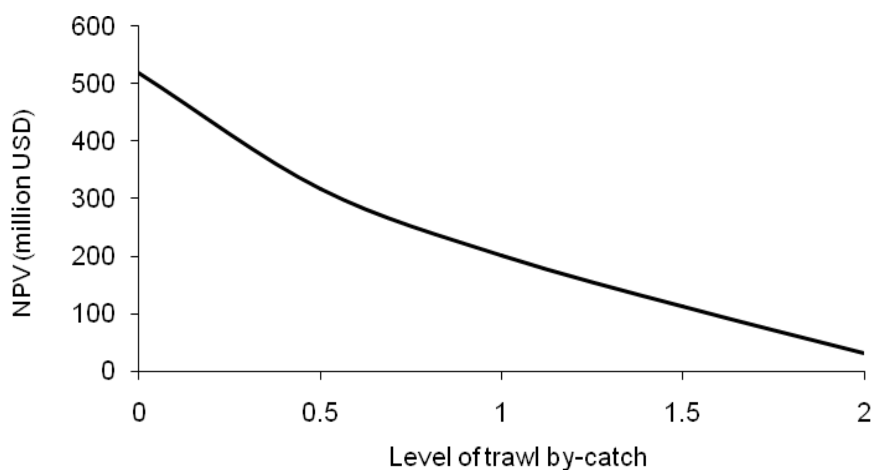

Figure 3. NPV of the artisanal sardinella fishery at increasing levels of trawl by-catch.

Not only do we see a decrease in the catch and the net present value, we also see a decrease in artisanal effort as a result of less sardinella being available to the artisanal fleet (Figure 4).

With no trawl-associated by-catch, an equilibrium effort of about 540,000 trips per year is the optimal amount. As by-catch increases, the equilibrium effort decreases, resulting in only a third of the amount of effort necessary at high by-catch levels (Figure 4). This decrease in trips per year would most probably result in a loss of jobs within the artisanal sector, or a decrease in income to individual fishers, if the total number of fishers employed remained constant. Given that the artisanal sector employs 80% of the all fishers, it seems likely that such a reduction in catch and effort would have a large socioeconomic impact on society.

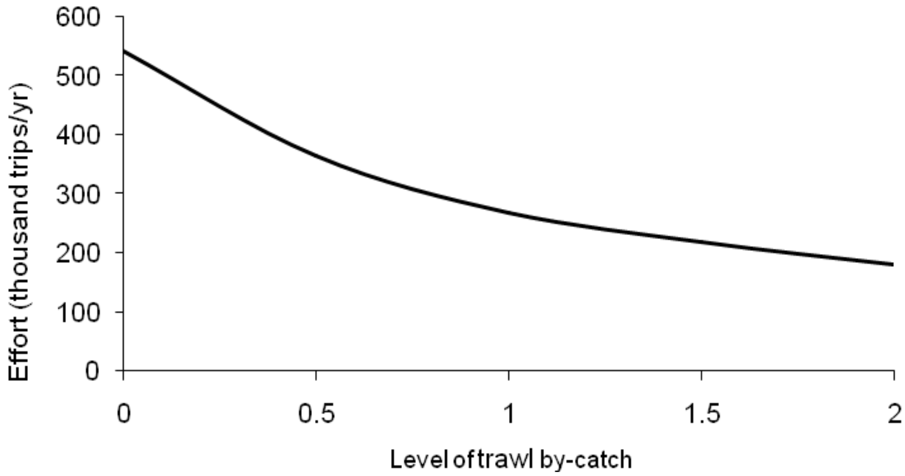

Figure 4. Equilibrium effort at increasing levels of trawl by-catch.

3.2. Spatial Conflicts

Cost of fishing was modified to simulate spatial conflicts. Everything being equal, lower cost of fishing is generally associated with higher effort, which results in a lower stock biomass. Figure 5 shows the equilibrium artisanal catch and effort at different costs of fishing. The higher equilibrium biomass associated with a high cost of fishing results in higher artisanal catches, but less effort and lower revenues (Figure 5). Summed over the 20-year simulation, we see a decrease in the NPV of the artisanal fishery, with the increase in costs associated with increased spatial conflicts (Figure 5).

It seems unrealistic to model the spatial conflict between artisanal fishers and trawl fishers while assuming that there is no by-catch of the trawl fishery. If the trawl fishery is fishing inshore, then the fleet is most likely catching sardinella. This is probably especially true given the lack of enforced rules regarding trawl mesh size (Nunoo et al., 2009), and limited coastal patrol monitoring. We therefore modelled the effect of a change in artisanal fishing costs if by-catch of sardinella was equal to 50% and 100% of the artisanal catch.

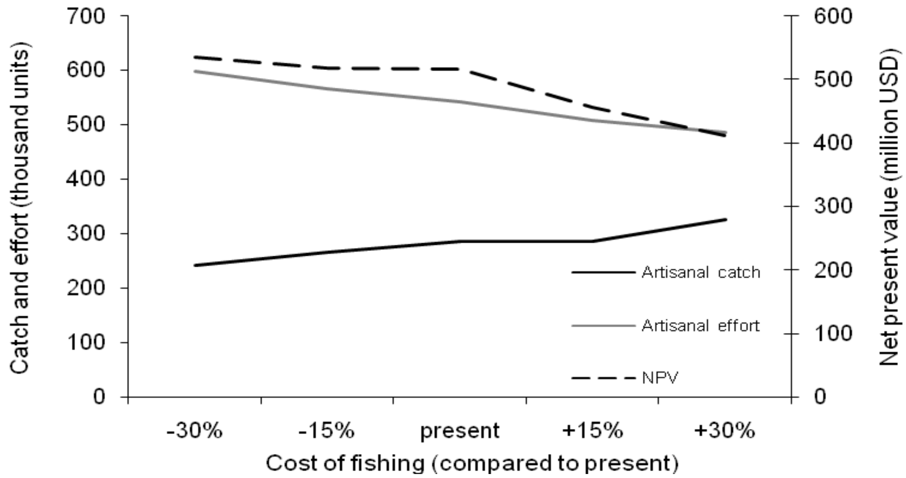

Figure 5. Equilibrium artisanal catch (tonnes), artisanal effort (trips per year) and NPV (million US$) at different costs of fishing.

The interesting comparison here is what we might consider the best and worst case scenarios for the artisanal fleet. The artisanal fleet is best off if there are no spatial conflicts with the trawl fleet (low cost) and there is no sardinella trawl by-catch (θ = 0). The artisanal fleet is worst off when there is a high amount of spatial overlap in the two fleets (high cost) and high level of trawl by-catch (θ = 0.5 and θ = 1). The difference between the low cost simulation, assuming minimal spatial conflicts/lost gear, and the high cost simulation, assuming higher amount of spatial conflicts/lost gear, is US$ 176 million, discounted over the 20 years (Table 2).

Table 2. Preliminary measurements of the fishery, given three scenarios

Variable (units)	Low cost, no by-catch	High cost, medium by-catch	High cost, high by-catch
Net present value of revenue (million US$)	236	85	60
Equilibrium artisanal catch (thousand tonnes)	128	99	28
Equilibrium artisanal effort (thousand trips/year)	333	160	59
Equilibrium sardinella biomass (thousand tonnes)	619	998	1017
Possible impact on biodiversity	Little or no impact	Negative	Highly negative
Possible impact on social welfare	Positive	Negative	Jobs: negative; discounted profit: positive

The artisanal fishery is regulated through formal and informal laws and thus regulation at this level may minimize the potential negative biodiversity impacts of the artisanal fleet on sardinella. The trawl fishery is indiscriminate in its catch, therefore catching juvenile sardinella, as well as potentially negatively affecting the genetic diversity and the variety of other species in the Gulf of Guinea.

4. CONCLUSION

Results from this Chapter suggest that the artisanal sector is overcapitalized, in that current fishing effort levels (estimated at 1.4 million trips in 2006 alone) could easily be cut in half, with sardinella catch increasing to 300,000 tonnes versus the present fishery catch estimated at 87,000 tonnes in 2006. This idea of cutting artisanal effort agrees with that proposed by Atta-Mills et al. (2004). While cutting effort in half may not appear socially feasible, it would result in much higher economic benefit to those currently fishing, and with higher catches, could lead to increased jobs in selling and processing. This may be especially true for women, who play a large role in processing and selling of the fish (Overå, 1993). The model's assumptions are fairly strict, in that we are interested only in the profits to the artisanal fishery, we assume that the biomass of the sardinella stock is influenced by only artisanal and trawl fishing effort, and the stock is modelled using the logistic function. Even if our simple model is only remotely correct, an annual yield of 300,000 tonnes should be possible. However, some reports suggest that sardinella are in decline and that the annual catch should be set at between 42,000 and 49,000 tonnes (Koranteng, 1997). While we admit that our model is simple, as recruitment is not incorporated into the stock dynamics, we believe this simplification is reasonable given that, even with catches of more than twice these recommendations, the stock appears to remain quite productive.

The model developed in this Chapter represents a very simplified picture of some possible interactions between the artisanal canoe fleet and the semi-industrial trawl fleet in Ghana. It is also important to note that, while this model is empirical, its results are illustrative only and should be used with caution.

Given the high growth rates of small pelagic fish, a sustainably managed sardinella fishery should be capable of yielding significant benefits in terms of contribution to small-scale fishers and to food security. The best case scenario for the artisanal fishers would be for management to limit by-catch by the trawl fleet, and to ensure that the trawl vessels remain offshore and do not venture into coastal waters. In this situation, enough sardinella is caught by the artisanal fleet alone to supply about half of domestic fish demand, while ensuring economic benefits to coastal communities, job security and a sustainable stock. Such a scenario could therefore be considered biologically, economically and socially positive. Although higher cost scenarios result in a higher overall sardinella catch (probably due to a more productive stock), they also result in less effort, which will not be seen positively given the high unemployment rate in fishing communities in Ghana.

One possible reason why the trawl and offshore tuna fisheries are currently prioritised over the artisanal sector could be the fact that money from high-value exported fish products is used for debt-reduction. This money does not trickle down to the fishers: or perhaps `trickle' down is precisely what it does. Instead of a flow of benefits to artisanal fishers, it seems that fishers are instead left with few domestic fish consumption options and little money. By favouring the export sector, of which the trawl fishery is a part, economic benefits appear to be the only positive outcome. High costs of fishing associated with lost/damaged gear in the artisanal fleet, and high by-catch of sardinella in the trawl fishery, could lead to decreased jobs and income to the canoe sector, as well as a possible decrease in food available for domestic consumption. In most circumstances, fisher income is based on a proportion of the catch value (Atta Mills et al., 2004), and therefore a decrease in artisanal revenues will most likely result in a decrease in fisher income. Furthermore, it is generally believed that trawl fisheries are particularly bad for biodiversity conservation, as their catches are indiscriminate (Nunoo and Evans, 1997; Maxwell et al., 2000).

Enhancement of food security and reduction of poverty are likely to remain crucial policies in sub-Saharan Africa and are predicted to play integral roles in biodiversity conservation strategies for both marine and terrestrial ecosystems (Pullin, 2004). At current population growth rate estimates, the 2030 Ghanaian population will require two times the current catch levels and fish imports, further illustrating that meeting domestic demand may have to shift management in favour of artisanal fisheries, as the industrial sectors supply foreign markets. The limited resources available for fisheries management in Ghana may be better spent on enforcing rules applied to the industrial sector (Marquette et al., 2002), while allowing the informal and traditional rules of canoe fisheries to enforce sustainable management policies at that level. One such management measure that should be easy enough to monitor at the village level is the adoption of bigger mesh sizes, as small mesh sizes appear to be a current threat to sardinella sustainability (Lenselink, 2002). It seems that in the case of Ghana's marine fisheries, biodiversity conservation and social well-being may not be at odds. Limiting by-catch in the trawl fishery, while promoting sustainable artisanal fisheries, may in fact be the best way for policy-makers to enhance social, economic and biological circumstances in coastal communities.

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APPENDIX: SOLVING THE OPTIMIZATION PROBLEM

What is the optimal artisanal effort that maximizes profit? A Lagrangian function is used to solve for the maximization problem, subject to the biological constraint $B_t \geq 0$:

$$L_t(B_t, E_t, y_t, \theta) = \delta^t \Pi_t(B_t E_t) + y_t \psi^-(B_t, E_t \theta) \tag{8}$$

where ψ represents the constraint function for which the modified Lagrange multiplier y_t is applied when $\psi < 0$. The multiplier is essentially the shadow price of the stock. As the stock size goes down (when growth minus catch is negative), this multiplier is activated, thus penalizing fishers for fishing too much. By expanding the profit and constraint functions we get the entire Lagrangian.

$$L_t(B_t, E_t, y_t, \theta) = \delta^t \sum_{t=1}^{T} \left(p_a q E_t B_t - \frac{c_a E_t^{1+b}}{1+b} \right) + y_t \left[rB_t \left(1 - \frac{B_t}{K} \right) - qE_t B_t - \theta q E_t B_t \right]^{-} \tag{9}$$

Effort Adjustment

Partial derivatives of the Lagrangian are calculated to compute model adjustment. The partial for artisanal effort adjustment is given as:

$$\frac{\partial L_t}{\partial E_t} = \delta^t (p_a q B_t - c_a E_a^b) + y_t H(\psi)^{-} \left[-qB_t - \theta q B_t \right] \tag{10}$$

In the adjustment equation, the term H has been added. This is a switch function, where $H(\psi)=1$ when $\psi<0$, and $H(\psi)=0$ otherwise. When the biological constraint is violated, $H=1$, and the penalty is applied.

Biomass Adjustment

$$\frac{\partial L_t}{\partial B_t} = \delta^t (p_a q E_t) + y_t H(\psi)^{-} \left[-r - \frac{2rB_t}{K} - qE_t - \theta q E_t \right] \tag{11}$$

Multiplier Adjustment

$$\frac{\partial L_t}{\partial y_t} = -H(\psi)^{-} \left[rB_t \left(1 - \frac{B_t}{K} \right) - qE_t B_t - \theta q E_t B_t \right] \tag{12}$$

Powersim software (Powersim Software AS, 2007) was used to run the optimization simulations. Third order, Runge-Kutta (fixed step) integration method was used, with 100,000 iterations implemented at each time step.

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