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The behavior of Atlantic cod, Gadus morhua, in an offshore net pen

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The behavior of Atlantic cod, Gadus morhua, in an offshore net pen

Abstract
Aquaculture is one of the fastest growing food producing sectors of the world, with an annual compounding growth rate of 8.8% (since 1970). In spite of the rapid growth, scientific and public concerns have arisen about the sustainability and environmental impacts of the industry, including aquaculture's dependence on wild fish products, eutrophication from animal waste and uneaten food, and escapement of genetically altered farming stock. The use of behavioral studies may help refine commercial aquaculture by obtaining information to design operations that optimize growth, and feed utilization, while increasing production and animal well being. The goal of this study was to design and develop a system for monitoring fine-scale fish behavior in an offshore aquaculture net pen, using a combination of ultrasonic telemetry and underwater video. Additionally, 32 Atlantic cod, Gadus morhua, were studied, via ultrasonic telemetry, to provide a preliminary analysis of activity rhythms, cage utilization, and feeding behavior within a net pen.

The first chapter provides a detailed description of a self-contained data collection system designed to study cod at a scale previously unavailable. Ultrasonic telemetry was used to monitor individual cod while a video system monitored group dynamics. A preliminary evaluation of the telemetry system documented high signal retention capable of logging fish positions every two seconds. Laboratory studies showed no influence of transmitter implantation on swimming speed, behavior or feeding. Additionally, our data documented that sampling rates over 10 seconds per location caused significant error in calculations of activity.

The second chapter provided an analysis of cod movement, daily activity rhythms, behavior, swimming speeds and cage use. Individual cod behavior remained independent of conspecifics and consisted primarily of "milling" behavior. Cod exhibited clear diurnal rhythms, with activity highest during daytime hours. Analysis of cage utilization documented inefficient use of the net pen; with individual space use limited to small overlapping areas within the bottom half of the net pen. Additionally, operational stresses were documented to elicit dramatic changes in behavior.

The third chapter used feeding behavior, along with stomach content analysis, to assess feeding efficiency. Aggressive feeding behavior was displayed in 42.7 +/- 4.6% of cod daily, while 25.8 +/- 3.7% of cod displayed no interest in feeding during a feeding cycle. Additionally, 31.5 +/- 4.5% of cod displayed an intermediate feeding behavior whereby fish moved into the feeding area but did not make vertical movements toward the feed source. Stomach content analysis revealed that 77.6 +/- 14.1% of cod stomachs contained recently consumed pellets. The combination of stomach content and ultrasonic telemetry data results suggests cod displayed multiple feeding strategies: aggressive, non-aggressive and none feeding, or scavenging.

Keywords
Agriculture, Fisheries and Aquaculture

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THE BEHAVIOR OF ATLANTIC COD, GADUS MORHUA, IN AN OFFSHORE NET PEN

BY

CHRISTOPHER B. RILLAHAN

B.S., University of New Hampshire, Durham 2002

THESIS

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Master of Science

In

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This thesis has been examined and approved.

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Professor of Zoology

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Professor of Zoology

Dr. Pingguo He
Research Associate Professor of Fisheries

10/14/2008
Date
DEDICATION

This thesis is dedicated to family and friends, both of whom provided me the support and confidence which has guided me in my life and allowed me to reach my goals.
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First, I would like to thank Dr. Win Watson for his time, effort, wisdom and technical knowledge. Win has pushed me to develop my understanding of fields far beyond traditional biology. Additionally I would like to thank my other committee members Dr. W. Hunt Howell, for his practical outlook and fish knowledge, and Dr. Pingguo He.

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TABLE OF CONTENTS

DEDICATION...........................................................................................................................................iii

ACKNOWLEDGEMENTS.......................................................................................................................iv

LIST OF FIGURES.....................................................................................................................................vii

ABSTRACT................................................................................................................................................ix

CHAPTER PAGE

INTRODUCTION.........................................................................................................................................1

1. A SELF-CONTAINED SYSTEM FOR OBSERVING AND QUANTIFYING THE BEHAVIOR OF ATLANTIC COD, GADUS MORHUA, IN AN OFFSHORE AQUACULTURE CAGE .........................................................................................12

2. THE BEHAVIOR OF ATLANTIC COD (GADUS MORHUA) IN AN OFFSHORE AQUACULTURE NET PEN .................................................................................................................................39

3. FEEDING BEHAVIOR OF ATLANTIC COD, GADUS MORHUA, IN AN OFFSHORE AQUACULTURE NET PEN ..........................................................................................................................66

CONCLUSIONS.........................................................................................................................................91

FUTURE STUDIES ...................................................................................................................................93

LITERATURE CITED.................................................................................................................................95

APPENDIX A IACUC APPROVAL LETTER ..........................................................................................100
LIST OF FIGURES

CHAPTER I

1.1 A schematic of the self-contained instrumentation buoy ..................................17
1.2 The layout of instrumentation on the net pen ..................................................20
1.3 The effects of sampling rate on calculations of activity .................................28
1.4 Correlation between sampling rate and activity .............................................29
1.5 Daily activity rhythm of two cod between August 24th and August 27th ..........31
1.6 Cage utilization of cod ..................................................................................32
1.7 Video analysis of cod feeding ........................................................................33
1.8 Telemetry analysis of cod feeding ..................................................................34

CHAPTER II

2.1 Diurnal activity of cod ...................................................................................48
2.2 Activity track of one cod during day and night hours ..................................49
2.3 Cage utilization of tracked cod .......................................................................50
2.4 Effects of artificial lights on activity ...............................................................52
2.5 Effects of artificial lights on behavior ..............................................................53
2.6 Densities effect on activity rhythms ...............................................................55
2.7 Densities effect on swimming behavior .........................................................56
2.8 Comparison of space use in multiple net pens .................................................58
2.9 Cumulative cage use of tracked cod ...............................................................59

CHAPTER III

3.1 Movement of a single cod during three hours of the day .............................73
3.2 Different feeding strategies exhibited by five cod during a single feeding bout ..74
3.3 Classification of cod stomach contents ............................................................77
ABSTRACT

THE BEHAVIOR OF ATLANTIC COD, GADUS MORHUA, IN AN OFFSHORE NET PEN

By

Christopher B. Rillahan

University of New Hampshire, December, 2008

Aquaculture is one of the fastest growing food producing sectors of the world, with an annual compounding growth rate of 8.8% (since 1970). In spite of the rapid growth, scientific and public concerns have arisen about the sustainability and environmental impacts of the industry, including aquaculture’s dependence on wild fish products, eutrophication from animal waste and uneaten food, and escapement of genetically altered farming stock. The use of behavioral studies may help refine commercial aquaculture by obtaining information to design operations that optimize growth, and feed utilization, while increasing production and animal well being. The goal of this study was to design and develop a system for monitoring fine-scale fish behavior in an offshore aquaculture net pen, using a combination of ultrasonic telemetry and underwater video. Additionally, 32 Atlantic cod, Gadus morhua, were studied, via ultrasonic telemetry, to provide a preliminary analysis of activity rhythms, cage utilization, and feeding behavior within a net pen.

The first chapter provides a detailed description of a self-contained data collection system designed to study cod at a scale previously unavailable. Ultrasonic telemetry was
used to monitor individual cod while a video system monitored group dynamics. A preliminary evaluation of the telemetry system documented high signal retention capable of logging fish positions every two seconds. Laboratory studies showed no influence of transmitter implantation on swimming speed, behavior or feeding. Additionally, our data documented that sampling rates over 10 seconds per location caused significant error in calculations of activity.

The second chapter provided an analysis of cod movement, daily activity rhythms, behavior, swimming speeds and cage use. Individual cod behavior remained independent of conspecifics and consisted primarily of “milling” behavior. Cod exhibited clear diurnal rhythms, with activity highest during daytime hours. Analysis of cage utilization documented inefficient use of the net pen; with individual space use limited to small overlapping areas within the bottom half of the net pen. Additionally, operational stresses were documented to elicit dramatic changes in behavior.

The third chapter used feeding behavior, along with stomach content analysis, to assess feeding efficiency. Aggressive feeding behavior was displayed in $42.7 \pm 4.6\%$ of cod daily, while $25.8 \pm 3.7\%$ of cod displayed no interest in feeding during a feeding cycle. Additionally, $31.5 \pm 4.5\%$ of cod displayed an intermediate feeding behavior whereby fish moved into the feeding area but did not make vertical movements toward the feed source. Stomach content analysis revealed that $77.6 \pm 14.1\%$ of cod stomachs contained recently consumed pellets. The combination of stomach content and ultrasonic telemetry data results suggests cod displayed multiple feeding strategies: aggressive, non-aggressive and none feeding, or scavenging.
INTRODUCTION

Aquaculture

Seventy of the world’s fish stocks are fully-exploited, over exploited, depleted or recovering from depletion (FAO, 2006). Despite this, the demand for edible seafood continues to rise as global population increases. The demand for edible seafood is projected to increase by 26% by 2010 (FAO, 2004). While traditional capture fisheries struggle to keep up, there becomes a supply-and-demand deficit.

To compensate for this demand, aquaculture production is rapidly increasing and is one of the fastest growing food producing sectors of the world (FAO, 2004). Since 1970 aquaculture landings have increased from 5.3% of fisheries landings, by weight, to 32.2% in 2000. Currently one out of every three fish eaten globally has been farm raised. Aquaculture has had an annual compound growth rate of 8.9% since 1970, compared with 1.4% for traditional fisheries and 2.8% for terrestrially farmed meat. In 2000, aquaculture production was 45.71 million metric tons (mmt), with a value of $56.47 billion (ww.fao.org).

Aquaculture landings are broken down into finfish (50.4% of production or 23.04 mmt), mollusks (23.5% or 10.73 mmt), aquatic plants (22.3% or 10.13 mmt) and crustaceans (3.6% or 1.65 mmt). Currently, 131 species of finfish are being grown, and this portion of the industry is dominated by Asian aquatic herbivorous finfish like cyprinids (68.2%), tilapia (5.5%), and other miscellaneous freshwater fish (10.4%).
While, thirty five species of marine finfish are grown, they only account for 4.4% of finfish production, by weight. Due to their high consumer demand marine carnivorous fish drive a high market price in European and North American markets. Thus, while carnivorous fish account for just 13% of total production, by weight, they yield 34.3% of the market by value (FAO, 2003).

Aquaculture in North America, largely the U.S., is a $1.24 billion industry. However North America only produces 1.2% (0.55 mmt) of the global aquaculture catch. While the U.S. has been increasing its production by 3.9% per year since 1970, they are still the second largest importer of seafood, leading to an estimated $6.8 billion trade deficit, as of 2002 (FAO, 2003).

Recently the U.S. formulated a national aquaculture policy to accelerate aquaculture production. One of the two main areas of focus was open ocean aquaculture (FAO, 2003). The development of appropriate science and technology to support open ocean aquaculture is paramount in the development of new, efficient, aquaculture techniques for this environment. The studies described in this thesis were driven, in part, by the need to understand more about the behavior and physiology of cod in offshore net pens.

History and Biology of Cod

The Atlantic cod, *Gadus morhua*, is a demersal gadoid species. Cod are primarily a marine, cold water finfish distributed on both sides of the North Atlantic. In the Northwest Atlantic their distribution ranges from Greenland to North Carolina. Cod have been regularly documented to attain lengths of 130 cm (51 inches) and 25-35 kg (55-77
lb); however individuals have been measured to reach up to 180 cm and 96 kg. Cod live about 20 years reaching reproductive age at 2-4 years. They are omnivorous feeders, consuming a variety of invertebrate and fish prey.

The Atlantic cod fishery has a very long and productive history. Basques and Nordic colonies were harvesting cod starting around 500-600 A.D. When the New World was discovered by Europeans, frequent stories of endless shoals of cod were reported back to Europe. The northern cod fishery started in the early 1500’s and by 1550 60% of fish eaten in Europe were Newfoundland salt cod (Kurlansky, 1997). The seeming endless supply of cod fueled European and colonial American industries for generations. As fishing technology increased from coastal handline fisheries to offshore trawlers, the cod fishery became the hallmark example of a fishery’s collapse. In 2003, 851,319 mt of Atlantic cod were harvested globally. This is a 78.4% decline from its pinnacle of 3.94 mmt in 1968 (FAOSTAT, 2005).

Within the U.S., cod stocks have also been affected by the collapse. U.S. landings have declined 75.4% from 1990 (43,491 mt) to 2003 (10,698 mt). Within the Gulf of Maine, NMFS (National Marine Fisheries Service) bottom trawl surveys have also documented record low levels of abundance and biomass (www.nefsc.noaa.gov). The social and economical implications of the collapse have hit local fishing communities very hard. Recently, Congress has begun to develop programs to help failing fishing communities through vessel buy-outs, job retraining and subsidized health insurance. In addition to these efforts, work continues to evolve in fisheries sciences, “smart fishing” technologies and aquaculture to revive the fishing industry. “The fishing industry of New
England has for over 400 years, been identified both economically and culturally with groundfishing” (www.nefsc.noaa.gov).

Unfortunately, New England fish production has recently faced another economic hardship. The farming of Atlantic salmon (Salmo salar), the region’s largest aquaculture industry, is facing economic difficulties due to the global increase in production and thus a decrease in market price. This has led them to diversify their farming interests. Currently the technology and interest are sufficient to farm cod. This is also beneficial because cod can be grown in traditional salmon cages, and some studies have shown cod can grow 2-5x faster in culture than in the wild (Chambers and Howell, 2006).

In Norway, the cod farming industry is also rapidly evolving and expectations are high. “Atlantic cod will be the dominant gadoid species in culture, and it is believed that production can reach levels similar to those of farmed salmon in 15-20 years” (Rosenlund and Skretting, 2006). While production of cod is still low, at 2,000 mt landed in 2003, Norway issued 500 cod farming licenses in 2005. Farmed cod landings are predicted to reach 140-180,000 mt by 2010, with Norway accounting for 50-60%, and the USA and Canada around 30%, of that total (Rosenlund and Skretting, 2006).

As previously described, the USA has developed a national aquaculture policy to accelerate the advancement of offshore aquaculture. The offshore environment is ideal for several reasons. First, inshore waters are commonly used for recreation, shipping and commercial fishing which may lead to conflicting interests and restrictions on aquaculture growth. Secondly, the offshore environment provides better water quality, better dispersion of farm effluent, more stable temperatures and more space for farming
(Chambers and Howell, 2006). However, the offshore habitat provides many new challenges in comparison with inshore aquaculture and the technology associated with fish farming in the open ocean is still being developed.

The Open Ocean Aquaculture (OOA) demonstration project, located at the University of New Hampshire, was established to develop technology and gather information relevant to the commercial production of cold-water fish and shellfish in the offshore environment. The overall goal of the OOA project is to stimulate the further development of commercial aquaculture in New England, thereby increasing seafood production, creating new employment opportunities, and contributing to economic and community development (www.ooa.unh.edu).

In the fall/winter of 2005 the first class of cod was harvested at the OOA study site located 13 kilometers off the New Hampshire coast. Preliminary data indicated that the fish had a 92% survival rate, a scope for growth (SGR) of 0.49% d\(^{-1}\) (which is comparable to previous laboratory studies) and no evidence of disease (Chambers and Howell, 2006). Cod were placed in the offshore cage in September 2003 at 45 g (mean weight) and harvested between August and December 2005 at 2-3 kg. While the data are promising, continued research needs to be accomplished to optimize the efficiency and production of this species. In particular more information needs to be gained concerning optimal feeding regimes, optimal rearing technology and relevant fish behaviors (Kjesbu et. al. 2006, Salvanes and Braithwaite, 2006, Rosenlund and Skretting, 2006).
Cod Behavior

While much is known about cod physiology and behavior in the laboratory, a limited number of studies have investigated general cod behavior in the wild. The lack of information is mainly due to the difficulty associated with studying these animals at the location and depths they inhabit. A few studies using ultrasonic telemetry and video have been used to investigate basic cod behaviors.

Cod in the wild are primarily benthic fish associated with complex habitat and areas of high relief (Gregory and Anderson, 1997; Cote et al. 2004). Although cod prefer rocky substrate, juvenile cod have been shown to aggregate over sand bottom (Laurel et al., 2004). Cod have small, localized home ranges varying between 1.0-77.33 ha (Hawkins et al., 1980; Cote et al., 2004; Neat et al., 2006; Espelande et al., 2007).

Cod are active both day and night, but they are typically more active during the day than the night. They tend to swim at relatively slow speeds throughout the day; rarely exceeding 1 BL/s (Gregory and Anderson, 1997; Lokkeborg et al., 1998; Cote et al., 2002; Kallayil et al., 2003). Daily activity is theorized to be associated with their dependence on vision for food searches (Lokkeborg and Ferno, 1999). When presented with food, cod were shown to have higher successful localization of bait during the day compared to night (Lokkeborg and Ferno, 1999).

Though several studies have clearly documented diurnal rhythms in cod, a majority of the studies were conducted during summer months, primarily due to the difficulty in conducting these studies during the winter months (Lokkeborg et al., 1998;
Only a few studies have investigated cod behavior during the spring, fall and winter. Cote et al. (2002) illustrated that daily activity was shown to deteriorate following the breakdown of the thermocline in the fall with nocturnal behavior observed in December.

While we know a little about cod behavior in the wild, our knowledge about the behavior of cod under aquaculture conditions is very limited. The extent of our understanding of cod behavior in a net pen comes from a basic description by Huse (1991) in the Handbook of Mariculture:

Cod do not cruise, but tend to stay relatively still or shift slowly about in the pens. Pen size does not seem to affect behavior or growth. Density experiments have not been carried out but no adverse effects have been observed at densities higher than what is normal in salmon net-pen rearing (>30kg/m$^3$). As a predatory fish with large prey on its menu, the frequency of food intake is not as pronounced as in fish feeding on smaller prey like salmon. Feeding once per day is sufficient with cod over 100 g, while cod larger than 500 g only require food every second day.

Behavioral Science and Aquaculture

Behavioral studies are important when trying to reduce stress and promote good living conditions for farmed animals (Juell and Westerberg, 1993). Several studies have illustrated the potential benefits of learning as much as possible about fish behavior under aquaculture conditions (Knight, 1985). Quantifiable changes in behavior have been documented in relation to operational and environmental stresses (Begout and Lagardere, 1993; Chandroo et al., 1999; Chandroo et al., 2005), density (Begout and Lagardere, 1993; Cooke et al., 2000; Anras and Lagardere, 2004), feeding (Smith et al., 1993; Juell and Westerberg, 1993; Juell et al., 1994; Clark et al., 1995; Greaves and Tuene, 2001)
and cage design (Anras and Lagardere, 2004). Chandroo et al. (2005) documented a stress response in rainbow trout during transportation; exemplified by swimming vigorously and remaining at an elevated activity state 48 hours after the incident. Similarly, striped bass expressed a 7-fold increase in swimming speed during periods of inclement weather (Begout and Lagardere, 1993). Likewise, initial investigations of stocking densities have documented detectable changes in behavior. Typically nocturnal turbot (Psetta maxima) showed a breakdown in activity rhythms at high densities (Begout and Lagardere, 1993). Diel behavior was exaggerated with increasing density in rainbow trout, resulting in increased average oxygen consumption (Cooke et al., 2000). Additional behavioral studies could provide the type of information that could lead to increased production yields and improved animal welfare condition. (Cooke et al. 2000)

The aquaculture environment poses several difficulties when studying fish behavior, such as large cage volumes, typically turbid water conditions and large numbers of fish. Typically researchers have relied on either video or biotelemetry to acquire information. Video has several advantages: 1) video equipment is relatively cheap and easy to use, 2) it allows the visualization of a large number of individuals at one time and, 3) it allows researchers to observe stimuli which may influence behavior (i.e. predator encounter, operational event, climatic event). For example, Clark et al. (1995) used a video system to study rejection rates of commercial and natural feed pellets in cod. This study showed that cod frequently rejected two types of commercial feed pellets but never rejected capelin (Mallotus villosus). This study documented the need for more palatable feed source to increase consumption and hence growth.
While monitoring fish behavior with video systems is fairly routine and easy to implement, it suffers from many disadvantages: 1) it is almost impossible to keep track of individual fish; 2) video cannot be obtained at night, and infrared sensitive cameras can only provide a very short viewing distance because saltwater absorbs light at that wavelength and; 3) quantifying fish behavior from videotapes is extremely difficult and time-consuming. The use of biotelemetry can overcome some of the pitfalls of video technology.

Biotelemetry consists of a transmitter attached to, or implanted in, an animal. The transmitter gathers information on location, movement, or physiological variables. This information is sent via radio or acoustic signals to a receiver where the information is integrated and stored (Baras and Lagardere, 1995). Only recently, researchers have begun to understand the benefits that telemetry can bring to the aquacultural environment (Baras and Lagardere, 1995).

Telemetry has the benefits of allowing an investigator to obtain data without the biases or stresses associated with handling and sampling (Bridger, 2001). Once an animal is “tagged”, constant data can be obtained with minimal impacts of human factors. While implantation of the transmitters is invasive, researchers have shown that this has no significant effect on swimming speed, growth or mortality (Cote et al. 1999). We believe that the benefits of this technology will allow us to understand the behavior of these organisms much better, especially if it is combined with routine video monitoring.

A major benefit of telemetry is the ability to monitor the activity of individual fish despite lighting or visibility conditions. In addition, because of the nature of the data obtained, it is possible to quantify many aspects of the behavior of the animal in question,
such as swimming speed, periods of the day when it is most active, and their spatial
distribution the cage. Unfortunately, telemetry systems also have their drawbacks: 1) they
are expensive, and more difficult to use than video systems; 2) fish have to be implanted
with transmitters, and this can limit the size of the fish that can be used and the number of
fish that can be tracked and; 3) most telemetry systems are not capable of collecting data
at a high enough speed, with a good enough resolution, to be practical in typical
aquaculture operations. Ideally both telemetry and video should be combined to acquire
a holistic view of animal behavior in a net pen.

Objectives

The first goal of this project was to construct a system capable of studying the
fine-scale movements of Atlantic cod in an offshore net pen using a combination of video
and ultrasonic telemetry. I then used the system I developed to investigate basic cod
behavior including daily rhythms, cage utilization and feeding. Chapter 1 reports on the
design of a self-contained instrumentation buoy capable of analyzing both individual and
group level behaviors. My major goal was to develop and evaluate this system to
determine its potential advantages and possible drawbacks compared with traditional
systems. Chapter 2 reports on how telemetry data can be used to investigate both spatial
and temporal aspects of cod behavior. My major goals included determination of the
types of daily rhythms of activity they expressed and the extent to which they used
different areas of the net pen. Additionally, I attempted to investigate if the addition of
operational stresses could illicit a measureable change in behavior, denoting a stress
reaction. Finally, Chapter 3 reports on the feeding behavior of cod within the net pen.
Within this study I investigated an assessment technique to evaluate feeding efficiency
within our culture system.
CHAPTER 1

A SELF-CONTAINED SYSTEM FOR OBSERVING AND QUANTIFYING THE BEHAVIOR OF ATLANTIC COD, *GADUS MORHUA*, IN AN OFFSHORE AQUACULTURE CAGE

Abstract

A self-contained data collection system is described that was used to study the fine-scale distribution and behavior of Atlantic cod (*Gadus morhua*) in an offshore net pen (Sea Station 3000). The entire system was housed in a modified U.S. Coast Guard (USCG) navigational buoy that was retrofitted for this purpose, and power was provided by a combination of eight 12V batteries, two solar panels and a wind generator. The behavior of the population as a whole, during daylight hours, was assessed using four waterproof cameras connected to a four channel digital video recorder. The behavior of individual fish was continuously recorded using a HTI model 291 ultrasonic telemetry system. Ultrasonic transmitters were surgically implanted into a sub-set of 4-12 fish during each study period. Laboratory studies showed no influence of transmitter implantation on swimming speed, behavior or feeding. Transmitters were programmed to “ping” at intervals of between 1.7 and 3.3 seconds and they typically lasted for about one month. The system successfully detected and plotted 84.9 ± 6.0% of transmissions, resulting in an average of 1283.4 ± 252.5 locations for each animal, during each hour of the study. This preliminary evaluation of cod behavior in a net pen demonstrates that
they are diurnally active and they have a tendency to mill about, rather than school. Cod predominately used the lower half of the cage, except when rising to the feeding area during periods of time when feed was delivered. The system that was developed proved to be ideal for investigating the behavior of fish within a net pen and it can be used with both inshore and offshore farms to gather behavioral data that can be used to improve the efficiency of aquaculture operations.

Introduction

Global aquaculture is a $63.3 billion dollar industry, yielding 45.5 mmt of seafood per year (FAO, 2006). While aquaculture continues to grow at a compounding growth rate of 8.8% per year (since 1970; FAO, 2006), scientific and public concerns have arisen about the sustainability and environmental impacts of the industry. Recent publications highlight several factors of concern, including aquaculture's dependence on wild fish products, eutrophication from animal waste and uneaten food, and escapement of genetically altered farming stock (Naylor et al., 2000; Powell, K., 2003; Naylor and Burke; 2005). While federal governments continue to embrace the growing industry, most aquaculture legislation highlights the need for continued research to reduce environmental impacts (Dept. of Commerce Aquaculture Policy, 1999, U.S. Ocean Action Plan, 2004, National Offshore Aquaculture Act, 2007).

One way to alleviate some of the issues described above is to use information regarding the behavior of farmed fish to design operations that reduce escapement and optimize feed utilization. For example, Juell and Westerberg (1993) found that the farmed salmon they tracked did not participate in 74.9% of the feeding bouts, suggesting
that an alternative feeding schedule might be more effective. Additional behavioral studies have revealed stress responses in farmed animals, due to environmental disturbances, farming operations or high stocking densities (Begout and Lagardere, 1993; Cooke et al., 2000; Anras and Lagardere, 2004; Chandroo et al., 2005). Using these behavioral data, fish farmers can then take appropriate steps to reduce stress of fish, that in turn could lead to enhanced growth and a better product.

While the aforementioned studies illustrate the practical implications of obtaining behavioral data about farmed fish, the difficulty in gathering such data in the field has impeded progress, especially with respect to offshore aquaculture operations. While monitoring fish behavior with video systems is fairly routine, and easy to implement, it has many disadvantages: 1) it is almost impossible to keep track of individual fish; 2) video cannot be obtained at night, and infra-red sensitive cameras cannot be used with marine fish because saltwater absorbs light at that wavelength; and 3) quantifying fish behavior from videotapes is extremely difficult and time-consuming.

The use of biotelemetry can overcome some of the pitfalls of video technology. A major benefit of telemetry is the ability to monitor the activity of individual fish despite lighting or visibility conditions. In addition, because of the nature of the data obtained, it is possible to quantify many aspects of the behavior of the animal in question, such as swimming speed, periods of the day when it is most active, and their spatial distribution the cage. Unfortunately, telemetry systems also have their drawbacks: 1) they are expensive, and more difficult to use than video systems; 2) fish have to be implanted with transmitters, and this can limit the size of the fish that can be used and the number of
fish that can be tracked; and 3) most telemetry systems are not capable of collecting data at a high enough speed, with a good enough resolution, to be practical in typical aquaculture operations. Due to these constraints, most studies to date, using ultrasonic telemetry, have focused on medium-scale movements of animals and data has been used to calculate home ranges and determine habitat use.

The overall goal of this investigation was to develop an integrated telemetry and video system that could be used to investigate the fine-scale distribution and behaviors of cod that are being raised by the UNH Open Ocean Aquaculture project (www.ooa.unh.edu) in a net pen located 13 km off the coast of NH, in the Gulf of Maine. This involved adapting a high frequency (307.2 kHz) telemetry system, initially developed for tracking fish in a freshwater habitat, for use in a marine environment, as well as taking advantage of existing video surveillance technologies that are designed for field use. Moreover, due to the offshore location of the study site, all systems needed to be powered using batteries, wind and solar power. In this manuscript, we describe our final product and present some representative data. The final system is based on a HTI (Model 291, Hydroacoustic Technologies Inc., Seattle, WA) biotelemetry system that uses four hydrophones, hard-wired to a receiver, to track fish implanted with a very small transmitter, in three dimensions. Positional fixes were obtained every two seconds, making it possible to very accurately calculate swimming speed and investigate very fine-scale movements. It was possible to use this high frequency system, rather than the ultrasonic telemetry systems typically used in the marine environment, because the net pen kept the fish in a small enough area that attenuation of the high frequency signals by seawater was not a problem.
Materials and Methods

Study Site

The UNH Open Ocean Aquaculture study site is located 13 km off the coast of New Hampshire and 1.5 km south of the Isle of Shoals (www.ooa.unh.edu). The site has a submerged grid system capable of mooring up to four cages and their associated surface support buoys. Atlantic Cod (*Gadus morhua*) are being raised in a 3000 m$^3$ Sea Station™ cage (25 m wide x 15.5 m deep; Net Systems Inc., Bainbridge, WA). One cohort (~30,000) of cod was raised in the pen from September 2003 to February 2006 and the other cohort of 50,000 juvenile cod (~50 grams) were transferred to the site for grow out in April of 2006. The data presented in this paper were collected from both groups of fish.

The exposed nature of the site required the design of a system to house the electronics while facing high seas (8+ m), high winds, and ice caused by sea spray. An independent self-contained system was created within a refurbished USCG, 6 x 20 LR navigational buoy (Fig. 1.1) moored on a 2-point mooring within the submerged grid network. The advantage of having an independent buoy system was its ability to be moored in a central location, giving researchers the ability to monitor multiple cages while also being able to disconnect from the site and tow it to protected waters during large storms. The disadvantage of this independent system was that the size of the infrastructure required to handle the sea conditions, and provide sufficient power, greatly surpassed the actual size of the electronics.
Figure 1.1. A schematic of the self-contained instrumentation buoy. A USCG navigational buoy was refurbished to serve as an independent fish monitoring buoy. Instrument cables from the cage plugged into a waterproof junction box (C), then cables transferred information to the instrumentation (A) or battery (B) silo. Solar panels and a wind generator charged the batteries located in silo B.
Monitoring Equipment

The Hydroacoustic Technologies Inc. (HTI) Model 291 Portable Acoustic Tracking System (Seattle, WA) was used to track fish in this study. This system was chosen for several reasons: 1) it uses fixed hydrophones connected directly to the receiver so the position of the fish being tracked can be accurately (sub-meter resolution), and rapidly (0.2-16 seconds per location); 2) the system is able to simultaneously track and plot the position of multiple fish in three dimensions; and 3) the tags used are small enough so that they can be easily implanted in juvenile cod. This HTI system uses small high frequency (307.2 kHz) transmitters designed for freshwater environments. In seawater these signals are significantly attenuated. However, because the fish are confined within a net pen, signal loss was not a problem.

A four hydrophone array was fixed to the netting forming the enclosure (Fig. 1.2). Hydrophones were hardwired, via 500 foot cables, to the surface buoy. A Dell Inspiron 600m laptop computer running AcousticTag software (Version 4, HTI) controlled the system and logged data.

To ensure the fish tracked via biotelemetry represent “stereotypical” fish behavior, a four channel digital video recorder (DVR; ID-400CD-SN, Compulan Centers Inc., Dallas, TX) was simultaneously used to log video data from four cameras. Three cameras were selectively placed around the cage to capture large-scale fish movements. One additional camera was placed on the surface buoy to log environmental conditions, boat traffic or any surface activity which may have elicited a response by the fish. Data were stored on an onboard hot-swappable 240 GB hard disk, which was sufficient to
store a week's worth of video data. The DVR was scheduled to record only during daylight hours to avoid unnecessary use of power or storage space.

A 2D-ACM acoustic current meter (Falmouth Scientific Inc., Falmouth, MA) was placed within the net to monitor current speed and direction, temperature and salinity. The current meter was hardwired to the surface buoy and data were stored on the laptop computer. HOBO temperature and light loggers (Onset Computer Inc., Bourne, MA) were placed within the cage to monitor light intensity and temperature. A wireless router (Linksys Co.) provided a close-range link between the on-board computer and DVR, and the research vessel used during the study. This allowed for system configuration, verification and data downloading without having to board the buoy.
Figure 1.2. The layout of instrumentation on the net pen. The SeaStation 3000 grow out net consisted of a steel central spar and surrounding rim. Rope stays and spectra net panels maintained the nets rigid structure. The net was equipped with 3 video cameras (eye icons) and four hydrophones (circles).
Power

The system was designed to autonomously collect video, telemetry and environmental data for approximately one week. In order to fill the power requirements of the electronics, a rack of eight, 110-Ahr batteries were installed in a separate battery silo of the buoy (Fig. 1.1). Four solar panels and a wind generator were installed on the buoy tower to supplement the battery power; however the demand of the system was much greater than the power they yielded. A plug on the surface of the buoy allowed for batteries to be recharged at sea, however complete recharging times ranged from 8-12 hours, therefore typically batteries were swapped out with fresh batteries, and brought to shore to be charged.

A power conditioning system controlled the flow of power within the system. A low voltage disconnect (LVD) protected the batteries from excessive drain by turning the system off when battery levels dropped below 9 volts. A fuse block and voltage regulator protected the electronics from amperage and voltage spikes when connected externally to a generator.

Surgical Procedure

At the offshore site, sentinel fish were captured from the net pen, slowly decompressed by bringing them to the surface at a rate of 5 m/hr, and brought on board the research vessel for surgery. Fish were anesthetized using MS-222 (50 ppm) and a small incision was made on the ventral side, posterior to the pectoral fins. An ultrasonic tag was then implanted into the abdominal cavity of the fish and two sutures were used to close the incision. HTI F-tags (9 mm diameter x 21 mm length; 2.2 g in air, 1.1 g in
Freshwater; duration: ~24 days) were used for smaller cod and HTI G-tags (11 mm diameter x 25 mm length; 2.4 g in air; duration: ~30-40 days) were used for larger cod. Tags did not exceed 2.5% of the body weight as recommended in the literature (Baras and Lagardere, 1995; Jepsen et al., 2002). Fish remained in the anesthesia recovery tanks onboard until fully recovered from surgery (~30 min) and then were returned by divers to the net pen. Fish were continuously monitored for the duration of the tag life, about one month. Cote et al. (1999) demonstrated that in juvenile cod implanted transmitters did not influence swimming, growth or mortality. Our tagging studies have yielded no incidences of infection or rejection. Mortality during tagging only occurred when a strong thermocline (<10°C) caused additional stress to the decompression and surgery. To minimize this additional stress, the decompression schedule was adjusted for longer decompression times below the thermocline (<~10 m) and an abbreviated decompression above the thermocline. An on-board chiller was added to provide a cooled water bath for the animals once on the boat. These adjustments to the decompression protocol eliminated further mortality incidents.

**Influence of transmitters on locomotion**

To determine the possible effects of surgery or transmitter implantation, the behavior of 12 fish was investigated in the laboratory before and after tag implantation. Cod (length: 25.89 ± 1.27 cm, weight 145.6 ± 34.3 g) were decompressed and transferred from the offshore site to the University of New Hampshire's Coastal Marine Laboratory, where they were maintained in a flow-through system from March through April of 2006 (water temperature: 4-5°C). Cod were hand fed to satiation every other day.
Four experimental trials were conducted in a shallow rectangular (2 m x 1 m x 0.5 m) water bath containing three 1 m circular raceways receiving flow through seawater (4-5°C). The experimental tank was draped in opaque plastic to isolate animals from visual disturbances, and the enclosure was kept on a 12:12 light:dark photoperiod. Three low light infrared video cameras were installed above each circular raceway to monitor fish activity, and a digital video recorder was used to store video data on hot-swappable hard disks.

One cod was placed in each raceway (1 meter circumference) and allowed to acclimate for a two week prior to tagging. Animals were fed 5 pellets (~2% B.W.) every other day. Following the acclimation period, animals were surgically implanted with a transmitter using the same protocol previously described. Fish were then returned to the raceways and their behavior and feed intake was monitored for one week after tagging.

Activity was determined by quantifying the number of laps an individual swam during the first 15 minutes of every hour. To determine the effect of implantation, activity was quantified for five days prior to tagging, during the acclimation period, and five days after tagging. To evaluate the potential effect of implantation on feeding, the feeding regime previously described continued throughout the duration of the experiment. Five pellets were hand fed to each fish on altering days. Uneaten food was removed three hours after feeding to determine daily food consumption. Feed intake was monitored for one week before and after tagging. A Paired Student’s T-Test was used to compare pre-implantation, control group, to post-implantation, experimental group, to determine individual changes in behavior relating to tagging.
Data Collection and Analyses

The monitoring buoy was deployed at the UNH Open Ocean Aquaculture site in July 2006. Twenty-two cod were tagged between July 31\textsuperscript{st}, 2006 and November 2\textsuperscript{nd}, 2006 to test system performance. Four cohorts of individuals were tracked sequentially (three in August, four in September, six in early October and then nine added in mid-October). Between 3 and 13 fish were tracked simultaneously. Fish were continuously tracked for the duration of the tag life, 10-30 days. Due to the nature of signal processing within the HTI telemetry system, each transmitter must have a unique pulse period. The pulse period of the transmitters were programmed to “ping” at various intervals ranging from 1.7-3.3 seconds.

Raw acoustic files were processed using a two step procedure within the HTI software suite. First, the noise was manually filtered within the MarkTag software (Version 4.0) by isolating repetitive signals based on the pulse periods of individual transmitters. Second, the data were imported into AcousticTag (Version 4.0) where signals from each hydrophone were examined. A three dimensional triangulation algorithm was applied to achieve a positional fix. Two restrictions were applied to the algorithm to reduce erroneous locations. First, locations were locally restrained within a grid surrounding the cage. Second, locations were restrained based on excessive speed of travel (locations were omitted if subsequent positions yielded swimming speeds >1.5m/s). Lastly, the system was allowed to linearly interpolate gaps in the data set, if the gap was less than 30 seconds. Interpolated values were marked and examined for validity and quantity after processing. Resultant data, consisting primarily of a time stamp and X, Y, Z coordinates, were exported to a Microsoft Access database.
Previous studies (Begout and Legardere, 1993; Lokkeborg et al., 2002) have demonstrated a negative correlation between the duration of the interval between successive positional fixes and calculations of swimming speed. That is, the longer the interval the more likely that the true path of the fish was not tracked, and thus distance traveled will be underestimated. In order to test this theory we calculated the distance traveled by a subset of the fish we tracked, while systematically removing points to simulate different sampling intervals. Swimming speed and distance traveled were calculated within a one hour sample of data for six individual cod (three with a pulse rate of 2 seconds per location, three with a pulse rate of 2.5 seconds per location). The data set was then systematically reduced to evaluate swimming speed and distance traveled at theoretical sampling intervals of 4, 8, 12, 16, 32, and 64 seconds. Five replicates from each individual were examined at the same time of day. A Tukey-Kramer multiple comparison test was performed to examine the statistical relationship between sampling rates.

Activity data (swimming speed) was also plotted to determine if cod had a tendency for higher activity in the day vs. the night. Selected periods of data were also visualized in 3D using Tecplot (Version 10, Tecplot Inc., Bellevue, WA) to determine spatial use of the cage during feeding and resting periods of the day or night. Finally, to test the performance of the system data files were analyzed for the number of locations obtained per hour, number of interpolated values and transmitter life span. To estimate signal loss, the number of locations obtained per hour was compared with theoretical estimates of the number of “pings” produced by the transmitter.
Results

Equipment Performance

Twenty-two cod were tagged between July 31st, 2006 and November 2, 2006 to test system performance. Transmitters lasted from 10-29 days, and variation in battery life did not appear to correlate with any known variables. Pulse periods of the transmitters were programmed to between 1.7 seconds and 3.3 seconds, yielding a maximum of 1,090 to 2,117 locations per hour. The system detected and plotted 84.9 ± 6% of the maximum possible number of locations, averaging 1,283.4 locations per hour (Range: 866 – 1,770), depending on pulse period. Reduction in sample number was correlated with increasing ambient noise due to boat depth sounders and increased wind noise. Interpolated values averaged 3.8 ± 2.7% of the data obtained.

Over four weeks of video data were obtained from the four cameras. However storage and processing of so much data proved to be difficult. The power consumption of the system allowed for data to be collected for ~5 days (3.5-8 days) depending on supplements from the solar and wind generators. Longer system running times correlated with periods of time when wind speeds were high, demonstrating that wind power was more efficient than solar.

Impact of tags on fish behavior

Laboratory studies demonstrated that implantation of transmitters had no significant effects on swimming (N=10, P=0.949, Student’s Paired T-Test) or feeding behavior (N=12, P=0.848). Prior to implantation animals traveled 49.08 ± 2.4 m/hr in the
day and 46.97 ± 3.51 m/hr at night, while following implantation they traveled 47.71 ± 3.25 m/hr (Day) and 48.91 ± 3.62 m/hr (Night), respectively.

In the field animals returned to “normal” behavior ∼20-30 minutes after being returned to the cage. No behavioral changes were observed over the course of the experiment. No significant difference was observed in distance traveled between day 1 (post-implantation) and day 7 (N=10, P=0.12, Tukey-Kramer multiple comparison test), day 1 and day 14 (N=10, P=0.995) or day 7 and day 14 (N=10, P=0.222). None of the tagged animals died during the course of the experiment.

Influence of sampling interval on calculations of activity

Systematic reductions in the sampling interval demonstrated that activity (i.e. distance traveled in body lengths per hour) was negatively correlated with sampling interval (Fig. 1.3). As the sampling resolution was reduced from 2 seconds to 80 seconds, calculations of distance traveled significantly decreased at intervals longer than 10-12 seconds. Reductions in sampling intervals resulted in an 8.4-55.8% decrease in distance traveled when increased from 2 second intervals to 12 and 64 seconds intervals.

Data obtained from the field showed no correlation between number of locations obtained per hour and either distance traveled or average swimming speed (Fig. 1.4). This indicates that sampling interval was not a source or error in our data set.
Figure 1.3. The effects of sampling rate on calculations of activity. Distance traveled calculations using the same data set, but sampled at different intervals. Data were obtained from two cod originally tracked using sampling intervals of 2 seconds and 2.5 seconds. Reductions in sampling intervals resulted in underestimations of distance traveled. Asterisks represent statistically significant reductions in distance traveled compared with baseline sampling, 2 or 2.5 seconds. Significant reductions in distance traveled occurred when sampling interval increased greater than 10 seconds from baseline.
Figure 1.4. Correlation between sampling rate and activity. Average swimming speed calculations compared with number of locations obtained within an hour of data. Correlation coefficients of the linear regressions are low indicating there was little relationship between the number of data points obtained in an hour and the mean swimming speed.
Behavior of cod in the net pen

In general, at the stocking density used (~3-5 kg/m³), cod within the net pen did not school and the behavior of individual cod did not correlate with the other cod. Cod were more active during the day then night (Fig. 1.5). Except for periods of feeding, they had a strong tendency to distribute themselves in the bottom half of the net pen and around the perimeter of the net (Fig. 1.6).

Daily video from two locations in the net pen demonstrated that many of the cod had a tendency to move from the bottom of the net into the water column near the feeding tube when food pellets were delivered. Such movements to the top of the cage were limited to times when food was presented (Fig. 1.7). Telemetry data of individuals matched that of the video; however the telemetry data also demonstrated that not every cod fed during a given feeding period (Fig. 1.8). Movements expressed during feeding had a distinct pattern. Cod would migrate vertically to the feeding tube then descend back to deeper water before making another feeding loop. Feeding loops were distinct from one another and are probably associated with ingestion of individual pellets.
Figure 1.5. Daily activity rhythm of two cod between August 24\textsuperscript{th} and August 27\textsuperscript{th} (A). There was a significant difference between swimming speeds during the day (0.48 ± 0.12 and 0.40 ± 0.16 BL/s) and night (0.23 ± 0.08 and 0.16 ± 0.07 BL/s) (P=0.014; Student’s Paired T-Test). Observation of fish tracks (B: top and C: side) showed greater use of the cage during day hours (gray) and slow, localized milling around behavior during the night hours (black).
Figure 1.6. Cage utilization of cod. Combined tracks of eleven cod for one hour, between 11:00am-12:00pm, demonstrating full use of the cage below the rim, but sparse excursions to the upper half of the net pen.
Figure 1.7. Video analysis of cod feeding. Two perspectives on a feeding event at 16:15. A camera mounted on the bottom of the cage, looking up (D-F) shows fish moving into the water column as feeding time nears, however the camera from the top of the cage looking down (A-C) shows no fish in the top half of the cage until food is presented.
Figure 1.8. Telemetry analysis of cod feeding. The tracks displayed are of two fish during one feeding event. Fish one (light gray) makes several feeding loops into the feeding area and maintains a position within the center of the cage while fish two (dark gray) remains along the rim of the cage, separated from any feeding activity.
Discussion

Despite the benefits that can be gained by using data from behavioral studies to improve the rearing of fish, comparatively few studies have been published on the subject, possibly due to the difficulties of obtaining relevant information (Baras and Lagardere, 1995; Cooke et al., 2000). The system described in this manuscript consists of a simple collection of off-the-shelf, commercially available products assembled and designed with the purpose of studying fish behavior. The purpose of this system was to provide information about fish behavior in an offshore aquaculture net pen, however the infrastructure of this system (i.e. buoy and power system) could be eliminated to study animals near-shore or within a laboratory. The use of both telemetry and video provided a balance of information about the fine-scale behaviors of individual fish and the large-scale movements of the whole population.

Large net pen dimensions and reduced visibility typically restrict video from being collected though the entire net pen. The analysis of video data illustrated that strategic placement of cameras is essential when determining research objectives. When studying feeding, two opposing cameras provided different details relevant to feeding behavior. The camera placed on the top of the net pen, next to the feed tube, provided video relevant to feeding intensity (Figure 7, A-C), while the camera on the bottom of the net pen, showed cod moving off the bottom hours prior to feeding, illustrating possible feeding anticipatory activity (Figure 7 D-F).

Most likely due to their benthic nature, cod predominately occupied the bottom surfaces and outer edges of the net pen. However, when food was presented fish moved
toward the top of the net pen. As fish became satiated, they reduced the frequency of vertical migrations to the top and eventually returned to the bottom. Identical behavior have been shown in salmon and used as a matrix for measuring in-situ hunger levels (Juell et al., 1993). We have successfully used software to digitize and quantify feeding intensity based on the position of fish within the net pen, and it is possible that the output of such a system could provide instantaneous biological feedback which can help aquaculture managers optimize feeding regimes while minimizing food waste.

Traditionally, ultrasonic telemetry, using tags transmitting at frequencies in the range of 70 kHz, has been used in the marine environment because frequencies in this range travel almost a kilometer underwater, while higher frequency signals are rapidly attenuated. While these systems are optimal for tracking large-scale movements of a variety of mobile species, they are of limited use for examining the small-scale, rapid movements of fish in a net pen for two main reasons. First, due to the size of the transducer required it is difficult to build tags that are small enough to use in juvenile fish. Secondly, no commercially available ultrasonic telemetry system is capable of the type of high resolution, 3D, and rapid tracking required for quantifying the movements of fish in a net pen. The HTI system we adapted for use in this investigation was optimal for our needs, even though it was originally designed for use in rivers and lakes. It provided an accurate representation of the swimming activity of cod in the large offshore net pen and we have also used it to track both cod and trout within much smaller (90 m³) pens inshore.
Previous studies have demonstrated that sampling intervals can influence the accuracy of swimming speed calculations; however, these studies sampled at intervals of 15-17 seconds (Begout and Lagardere, 1993; Lokkeborg et al., 2002). Lokkeborg et al. (2002) demonstrated, in field measurements of cod that increasing the sampling interval from 17 seconds to 34 and 68 seconds resulted in a 30-50\% decrease in calculated swimming speed. Similar reductions in sampling speed from 12 second intervals to 32 and 64 seconds, within our system, demonstrated a reduction in activity from 19-51\%, matching the results of their study. Sampling rates below 12 seconds resulted in only an 8\% reduction in activity when using two second intervals compared to 12 seconds. These results indicate that it is possible to use sampling intervals as large as 10 seconds, which will conserve battery life and thus extend tag life, while at the same time providing data that are as accurate as can be obtained at smaller sampling intervals. However, it is recommended that the sampling interval be adjusted to the swimming behavior of the species in question, as well as the type of information that is desired. For example, the milling behavior, typical of cod (Figure 5), is characterized by random directional swimming, which may provide a higher degree of error at larger sampling intervals due to the increased likelihood of overlooking frequent loops within the track. In addition, lower resolution will reduce the likelihood of capturing fine-scale events, like feeding, prey capture, predator avoidance or burst swimming. When examining feeding behavior in wild cod, Lokkeborg et al. (2002) documented how longer sampling interval showed cod swimming straight to the food source, whereas higher resolution data illustrated cod swimming downstream of the odor plume in a zigzag search pattern. Furthermore, longer sampling intervals will average instantaneous swimming speeds reducing the resolution
of fine-scale accelerations and speed changes. Short burst of high speed have been documented to have exponential energetic consequences (Brett and Groves, 1979; Jobling, M., 1985; Webber et al., 1998).

Although behavioral studies have been limited in full-scale aquaculture operations, it is hoped that the evolution of new technologies, such as those described in this paper, will enable researchers to gather real-time information about fish welfare. Such studies will allow for the development of fish rearing technologies relevant to feeding behavior, activity patterns, density effects, cage utilization and design, as well as the effects of various operational and environmental parameters. Understanding the dynamics of fish behavior will aid in animal rearing by minimizing stress, increasing animal well-being and optimizing production.
CHAPTER 2

THE BEHAVIOR OF ATLANTIC COD (GADUS MORHUA) IN AN OFFSHORE NET PEN

Abstract

Despite the rapid growth in cod aquaculture, relative little is known about their basic behavior within net pens. This manuscript provides information on cod movement, daily activity rhythms, behavior, swimming speeds and cage use. Individual cod behavior remained independent of conspecifics and consisted primarily of “milling” behavior. Cod exhibited clear diurnal rhythms, with activity highest during daytime hours (17.83 ± 5.5 cm/s; 0.57 ± 0.18 BL/s) compared with nighttime hours (6.57 ± 0.53 cm/s; 0.2 ± 0.03 BL/s). Analysis of cage utilization documented inefficient use of the net pen, with individual space use limited to small overlapping areas within the bottom half of the net pen. The addition of operational stresses elicited dramatic changes in behavior. Periods of crepuscular illumination, with artificial lighting, increased cod activity 66.4% - 202.6%, compared to day and night level, respectively. Similarly, high density rearing resulted in the breakdown of daily rhythms, and the establishment of schooling behavior. The results of this study document that behavior can provide important information relevant to the future development of net pen design, optimal stocking densities, feeding and light regimes, leading to increased production efficiency and animal welfare.
Introduction

Cod aquaculture is predicted to grow to 140-180,000 tons/yr by 2010, and reach production levels similar to salmon in the next 15-20 years (Rosenlund and Skretting, 2006). While there is optimism about the future of cod aquaculture, and production goals have been set, relatively little is known about cod behavior in an aquaculture setting (Kjesbu et al, 2006). Studies of cod behavior in the wild indicate that they are primarily diurnal (Kallayil et al., 2003; Cote et al., 2002; Neat et al. 2006; Lokkeborg et al. 1998; Lokkeborg and Ferno, 1999), although they will occasionally express bouts of activity at night (Kallayil et al. 2003; Lokkeborg and Ferno. 1999). In general, when active, cod swim in a pattern that is often termed “milling” behavior (Huse, 1991). Finally, they have small home ranges (Espeland et al. 2007; Neat et al. 2006; Cote et al. 2004) and show associations with complex habitat and areas of high relief (Gregory and Anderson, 1997; Cote et al., 2004).

The aim of this study was to learn more about the behavior of cod in an aquaculture setting, with the long-term goal of using behavioral data to improve the efficiency of cod farming. Recent studies using telemetry and video technology have greatly expanded our understanding of the “normal” activity of fish in the wild, as well as the complex dynamics of fish behavior under farming conditions (Begout and Lagardere, 1993; Juell and Westerberg, 1993; Baras and Lagardere, 1995, Bridger et al., 2001). In this study we used both a very high resolution telemetry system and video methods to investigate the behavior of cod (*Gadus Morhua*) that were being raised in a net pen, (3,000m³ Sea Station), 13 km off the coast of NH.
The analysis of activity rhythms provides a clear example of how the behavior of fish will change in an aquaculture setting. For example, while there have been several reports of daily rhythms documented in farmed fish (Spieler, 1990; Begout and Lagardere, 1993; Cooke et al., 2000, Begout Anras and Lagardere, 2004), daily rhythms of turbot (*Psetta maxima*) have broken down at high densities, resulting in consistent, erratic activity (Begout and Lagardere, 1993). Similar changes in behavior have been documented in relation to climatic (Begout and Lagardere, 1993) and operational events (Chandroo et al. 2005). These distinct changes in behavior can serve as an indicator of stress, or sub-optimal growing conditions. Additionally, natural activity rhythms should be coordinated with feeding schedules to increase production and decrease food waste (Smith et al., 1993; Sanchez-Vazquez and Madrid, 2001). Lastly, knowledge of seasonal behavior rhythms has also been shown to have potential benefits. For example, Bridger et al. (2001) found that escaped steelhead trout had high site fidelity during the summer, and low site fidelity during the fall. Clearly, this type of information could help mitigate the effects of unintentional escapes.

Chapter 1 of the thesis described a system for studying cod in an offshore aquaculture net pen with high temporal and spatial accuracy. The objective of this study was to provide an initial descriptive analysis of "normal" behavior of cod in an aquaculture environment and provide a baseline for future work. Observations of activity when fish were grown at a high density and exposed to artificial lighting revealed some very interesting changes of behavior that should be taken into account when attempting to optimize cod farming operations. Finally, an analysis of cage utilization by cod suggests
that net pen design could be improved by taking into account the unique behaviors expressed by different fish species.

Materials and Methods

Study Site

The University of New Hampshire Open Ocean Aquaculture (OOA) project study site is located 13 km off the New Hampshire coast and 1.5 kilometer south of the Isle of Shoals. The OOA study site has a submerged grid system capable of mooring four cages and multiple support buoys. The first cohorts of 30,000 Atlantic Cod (*Gadus morhua*) were raised in a 3000 m$^3$ Sea Station™ cage (25 m wide x 15.5 m deep; Net Systems Inc., Bainbridge, WA) between September 2003 and February 2006. Following the harvest a second group of 50,000 cod were stocked in April 2006 with harvest planned for summer of 2008. The Sea Station 3000 cage was submerged so that the top of the cage was 15 meters underwater and the bottom was 30 meters from the surface. For additional information on infrastructure, grow out, and species performance, see Chambers and Howell (2006) or visit www.ooa.unh.edu.

Telemetry Equipment

The HTI model 291 ultrasonic telemetry system (Hydroacoustic Technologies Inc, Seattle WA), and associated ultrasonic tags, were used to continuously record the positions of cod within the net pen, as described in detail in Chapter 1. In brief, this system consisted of four hydrophones attached to the net pen and hardwired to a receiver on the surface. An acoustic receiver and a laptop computer, used to control the receiver and store data, was housed within an automated feed buoy (described by Chambers and Howell, 2006) during the 2004 season, then as part of a multi-system monitoring buoy in
2006 (Chapter 1). The HTI system was chosen due to its: 1) small ultrasonic transmitters; 2) ability to track multiple fish simultaneously in 3 dimensions; and 3) high spatial and temporal resolution.

The HTI transmitters used (F and G models) were programmed to transmit every 1.7-3.3 seconds. All data was stored on the laptop computer and downloaded from the study site weekly.

**Surgical Procedure**

At the offshore site, 10-15 cod were captured by divers, removed from the grow-out net and placed within a decompression cage. The fish were slowly brought to the surface, at a rate of 3 meters every 30 minutes and placed within a temperature controlled, aerated tank on-board the research vessel. The fish were anesthetized with MS-222 (50 ppm) and a small incision was made in the ventral side, posterior to the pectoral fins. An ultrasonic transmitter was then implanted into the abdominal cavity of the fish and two sutures were used to close the incision. HTI F-transmitters (9 mm diameter x 21 mm length; 2.2 g in air, 1.2 g in freshwater; duration: ~30 days) were used for smaller cod and HTI G- transmitters (11 mm diameter x 25 mm length; 1.9 g in freshwater; duration: ~30-50 days) were used for larger cod. Transmitters did not exceed 2.5% of the body weight as recommended in the literature (Baras and Lagardere, 1995; Brown et al., 1999; Jepsen et al., 2002). Fish remained in an anesthesia recovery tanks onboard until fully recovered from surgery (~ 30 min) and then returned to the net pen. Chapter 1 demonstrated that there was no significant effect of the transmitters on the locomotory behavior or feeding of cod in the laboratory, and no long-term change in behavior of tagged animals in the field.
1.1 Evaluating Baseline Behavior

To determine "normal" or baseline behavior of cod within the submerged net pen, five cod (mean length: 31.4 ± 1.7 cm) were tagged in early September, 2004. Positions of these sentinel cod were monitored continuously for 9 days. Cod were fed once daily between 1100 and 1230h, at ~1.5% body weight per day. Density of fish was approximately 3.2 kg/m³, and water temperature averaged 9.73 ± 0.4°C at 20 meters.

1.2 Effect of Artificial Lights

Three 400W metal halide lights, each producing 90 lm W⁻¹, were installed on the net pen to artificially extend the day length, and delay sexual maturity (Hansen et al., 2001; Taranger et al., 2006). Lights were used from 0400-0800h and 1600-2000h. Light levels ranged from 2 to 600 Lux, depending on location within the cage and time of day (Chambers and Howell, 2006).

To monitor the effects of this potential operational stress on the cod, five cod (mean length: 38.4 ± 2.6 cm) were tagged in mid-November of 2004. Positional information was recorded continuously for 9 days using the same technique as described above during the period of artificial illumination. Activity and behavior were compared between fish tracked in September, without lights, and the November cohort, exposed to lights, to evaluate the impact of this operational stress. The same feeding regime was used as in the "control" study where feed quantity was adjusted to ~1.5% body weight per day. The stocking density of the fish had risen to 4.8 kg/m³. Daily water temperature averaged 8.5 ± 0.1°C at 20 meters.
Trial 2

2.1 Effect of Density

To evaluate the impact of fish density on swimming behavior, 50,000 juvenile cod (31.5 g mean weight) were stocked into a 600 m³ small mesh nursery net within the Sea Station 3000. The goal was to grow the fish out to 150g before releasing them into the larger cage, to minimize the potential for escapement through the larger mesh size of the grow-out net. Stocking densities were allowed to rise in the nursery net from an initial density of 4.2 kg/m³ in April to 17 kg/m³ on August 1st and finally to 48.5 kg/m³ on October 5th, just prior to the release. Upon release into the grow-out net, in mid-October, the stocking density dropped to 2.75 kg/m³ due to the larger volume of the grow-out cage.

A total of 22 cod (mean length: 26.7 ± 2.5 cm) were tracked between August and November. Four groups of individuals were tracked sequentially (three in August, four in September, six in early October and then nine added in mid-October following the release from the nursery net). Fish were fed twice daily at 1000 and 1600h at 1% body weight per day. Feed amount was adjusted monthly to account for growth. Daily water temperature was 9.5 ± 0.7°C in August, 12.7 ± 1.3°C in September, and 11.7 ± 1°C in October, at 20 meters.

Data Analysis

Positional data from all studies consisted of 3-dimensional Cartesian coordinates (X, Y, Z) and a time stamp. Instantaneous swimming speed was calculated based on the duration of time between two locations. For most analyses, swimming speed was
averaged into one hour bins. The graphics program Tecplot (Version 10, TecPlot Inc., Bellevue, WA) was used to visualize swimming patterns.

Volume calculations were based on the construction of a three dimensional grid system (80 ft. x 80 ft. x 60ft.) created around the study area. The grid was divided into 1 cu. ft units. The AcousticTag software calculated a presence/absence dataset based on the positional data overlaid onto the grid. Grid units denoted with a presence value were summed to calculate a total volume of space used by a fish, or group of fish, per unit time. All volume calculations were converted from cubic feet to cubic meters for analysis.

All statistical tests were performed using Instat (GraphPad Software Inc., La Jolla, CA). All averages, unless indicated, are mean ± 1 S.D.

Results

Trial 1.1: Baseline Behavior

The cod tracked in this study exhibited clear diurnal rhythms (Fig. 2.1). Activity was highest in the early part of the day, remained high throughout most of the day, then decreased in late afternoon, and was consistently low during nighttime hours. Swimming speeds were significantly higher during daylight hours (1000-1600h; 17.83 ± 5.5 cm/s; 0.57 ± 0.18 BL/s) than nighttime hours (2200-0400h; 6.57 ± 0.53 cm/s; 0.2 ± 0.03 BL/s) (Paired Student’s T-Test, P= 0.0088, N=5). While swimming speeds at all times of day remained relatively low (averaging 11.5 cm/s ± 2.47 cm/s; 0.37 ± 0.08 BL/s) cod exhibited burst swimming up to 186.98 cm/s (5.84 BL/s). However, these high swimming speeds were rare in our study. Cod spent 95.7-99.4% of their time swimming under 1 BL/s.
The activity of individual cod was independent of conspecifics, and most consisted of “milling” behavior. Milling behavior was defined as swimming with continuous variation in swimming speed and directionality. Higher swimming speeds during the day were associated with greater use of the cage, while lower night activity caused the fish to be localized in smaller discrete locations (Fig. 2.2). Cod were mostly localized near the rim and lower half of the cage, which matches diver and video observations. Cod were rarely observed in the top half of the cage, except during feeding events. They spent 96.99 ± 8.45% of their time in the bottom half of the net pen. While the average individuals’ daily volume use (333.84 ± 40.79 m$^3$) was ~10% of the total cage volume, individual volumes were heavily overlapping, demonstrating inefficient use of the net pen (Fig. 2.3).
Figure 2.1: Diurnal activity of cod. Average hourly swimming speeds of five cod demonstrating diurnal circadian rhythms (A). Cod showed significantly higher activity during daylight hours than night hours (shaded bars) (B). Mean swimming speeds of five cod, over a period of five days, during the day vs. night hours.
Figure 2.2: Activity track of one cod during day (grey track) and night (black) hours from a top (A) and side (B) perspective.
Figure 2.3: Cage utilization of tracked cod. Cumulative space occupied by five cod over 24 hours from a side (A) and top (B) perspective. Cod primarily used areas near the rim and outer regions of the cage. Cod rarely moved to the upper half of the cage, with the exception of feeding periods, denoted by the asterisk.
Trial 1.2: Effects of Artificial Lights

Cod reacted dramatically to artificial lights. While their daily rhythms persisted, and swimming speeds during day (17.49 ± 4.5 cm/s; 0.46 ± 0.13 BL/s) and night (9.61 ± 2.1 cm/s; 0.25 ± 0.06 BL/s) showed little variation from the previous experiment, swimming speed during artificially lit periods (29.09 ± 7.9 cm/s; 0.75 ± 0.16 BL/s) was significantly greater than during the day or night, increasing 66.4% and 202.6% respectively (Repeated Measures ANOVA, P= 0.0011, N=5) (Fig. 2.4). Average hourly swimming speeds during lighted periods ranged from 7.1 cm/s (0.19 BL/s) to 74.1 cm/s (1.72 BL/s). Excessive swimming speeds recorded during lighted periods consisted of continuously elevated average swimming speeds, not more frequent or excessive bursts of swimming (maximum burst=201.3 cm/s or 5.44 bL/s), which would increased the overall average. As in the previous experiment, Trial 1.1, increased activity corresponded with increased area of use of the cage, however movement was still localized to the rim and outer areas of the net (Fig. 2.5).
Figure 2.4: Effects of artificial lights on activity. Average hourly swimming speed of five fish during the day (open bars), night (dark grey) and periods of time when artificial lights were turned on (light grey). A. Representative data from five fish over three days. B. Mean data for 5 fish over five days.
Figure 2.5: Effects of artificial lights on behavior. A representative track of one cod during one hour of artificial light from the side (A) and top (B) of cage. Activity shows increased movement around net compared with day and night tracks.
Trial 2.1: Effects of Increased Density

Cod at low densities within the nursery net behaved very similarly to the fish previously described in Trial 1. They were most active in the day, they used the same areas of the pen, most activity consisted of “milling” around, and fish did not appear to be strongly influenced by the fish around them. Rarely did fish swim in a full circle inside the net pen, and there was little evidence of schooling. However, as the fish grew, leading to an increase in biomass density, there was a gradual, yet discernable change in their behavior (Fig. 2.6). At a low density (~20 kg/m$^3$) cod swam significantly faster during the day (11.14 ± 3.47 cm/s, 0.45 ± 0.16 BL/s) than night (6.60 ± 1.98 cm/s; 0.27 ± 0.09 BL/s) (Paired T-Test, P= 0.037, N=4). However, at higher densities (~32 kg/m$^3$) swimming was more consistent, with no statistical difference between day (13.14 ± 1.64 cm/s; 0.54 ± 0.09 BL/s) and night swimming speed (12.00 ± 2.81 cm/s; 0.49 ± 0.13 bL/s) (Paired T-Test, P= 0.379, N=3). The disintegration of daily rhythms coincided with a shift from milling to schooling behavior, consisting of synchronized and polarized swimming patterns (Fig. 2.7).

The release of the cod from the nursery net to the grow-out net represented an instant reduction in density from 48.5 to 2.75 kg/m$^3$. Individuals tracked within the grow-out net returned to stereotypical behavior, with the establishment of daily rhythms (Day swimming speed: 10.42 ± 1.54 cm/s, 0.38 ± 0.06 BL/s; Night 6.29 ± 1.39 cm/s, 0.23 ± 0.06 BL/s; Day swimming speed vs. night: Paired T-Test, P= 0.0003, N=9) and the breakdown of schooling (Fig. 2.7).
Figure 2.6: Densities effect on activity rhythms. Average hourly swimming speed of two cod for four weeks (A-D) prior to release from the nursery net. Disintegration of daily rhythms coincided with increasing density from \(\sim 20 \text{ kg/m}^3\) (A) to \(\sim 32 \text{ kg/m}^3\) (D).
Figure 2.7: Densities effect on swimming behavior. Behavior of three fish during medium density (A; 17 kg/m$^3$), high density (B: 48.5 kg/m$^3$) and low density (C: 2.75 kg/m$^3$). Fish behavior changed from milling around at low (C) and medium densities (A) to schooling behavior at a high density (B).
Volume use doubled in individuals upon release from the nursery net (177.79 ± 25.68 m³, N=7) to the grow-out net (349.85 ± 84.42 m³, N=13; P < 0.0001), suggesting cod were volume limited in the nursery net. Volume use data obtained from fish in the grow-out net in 2006 were not statistically different from those in 2004 (P= 0.0416, Fig. 2.8). Again, fish were primarily found associated with the lower half of net and the rim (Fig. 2.9). Volume used by the tagged fish was ~56% (1689.8 cu. m.) of total cage volume, indicating inefficient use of total cage volume. Plotting the sequential accumulated space use from one to 13 fish shows an asymptotic relationship where a limited number of animals define the space used by the population (Fig. 2.9).
Figure 2.8: Comparison of space use in multiple net pens. Average daily space use of individual cod during 2004 (N=10), nursery net 2006 (N=7) and grow-out net in 2006 (N=13). Data are given in mean ± 1 standard deviation.
Figure 2.9: Cumulative cage use of tracked cod. Daily volume use of one fish (Side, A; Top, B) compared to 13 fish (Side, C; Top, D) illustrating tendency to occupy areas near the rim and the bottom half of the cage. Sequential accumulated space use by more and more fish shows an asymptotic relationship where a limited number of animals define the space used by the population (E).
Discussion

Baseline Activity

Swimming speeds within this study closely correspond with data from previous studies of wild cod. Swimming speeds ranged from 10.4 - 17.8 cm/s (0.38 – 0.57 BL/s) during the day, to 6.3 - 9.6 cm/s (0.2 – 0.27 BL/s) during night time hours. Daily swimming speeds of wild cod rarely exceed 1 BL/s (Gregory and Anderson, 1997; Lokkeborg et al., 1998; Cote et al., 2002; Kallayil et al., 2003), with field measurements ranging from 9 to 17 cm/s (Lokkeborg et al., 1998; Cote et al., 2002). Lokkeborg and Ferno (1999) documented cod activity increasing between 0400 and 0600h, remaining active until 1400h, then reducing activity though the afternoon into evening. Swimming speeds in the wild range from 15-40 cm/s during the day compared with 2-5 cm/s at night (fish size: 45-63 cm; Kallayil et al., 2003). While activity at night is reduced, cod are still active during this time, and have been shown to feed at night in the wild (Lokkeborg et al., 1998).

While the pattern of activity, mean swimming speeds and range, in wild cod closely matches activity patterns documented within this study, our system, with its high sampling rate, documented burst swimming speeds of up to 201.3 cm/s (5.44 BL/s). While excessive bursts in activity were rare, such events may be reactions to operational events, predators or agonistic/aggressive behaviors. Additionally, these bursts of activity carry a disproportionally high energetic cost (Brett and Groves, 1979; Webber et al., 1998).

Evidence of diurnal rhythms, similar to those presented in this study, have been documented for cod in the wild (Gregory and Anderson, 1997; Lokkeborg et al., 1998;
Lokkeborg and Ferno, 1999; Kallayil et al., 2003; Cote et al., 2004). However, these rhythms appear to be fairly plastic, changing with the season and feeding schedules. For example, Cote et al. (2002) showed that diurnal activity was higher in September and October than December, when cod appeared to become more nocturnally active. Similarly, Kallayil et al. (2003) documented increased activity at night when baited gillnets were presented within the study area. While, our study clearly demonstrates diurnal rhythms under normal fish farming conditions, further investigations needs to be conducted into factors affecting these rhythms, primarily season and feeding regime, such as those shown for the European seabass (*Dicentrarchus labrax* L.) that alter their activity rhythms depending on feeding schedules (Azzaydi et al., 1998).

**Use of space within the net pen**

In this study, cod typically expressed localized movements, and they were most often associated with the bottom and rim area of the net pen. While we were only able to track 32 individual cod, video and diver observations have confirmed that these individuals provided an accurate representation of the population. Cod in the wild are primarily benthic fish, and juveniles have shown a preference for complex habitats and areas of high relief (Gregory and Anderson, 1997; Cote et al., 2004). These tendencies are likely to drive cod within the net pen to stay close to the bottom of the net, as well as near areas of relative complexity (i.e. the rim and bottom of the spar). Laurel et al. (2004) documented cod altering behavior to form more aggregated groups over less complex habitat (sand) compared to eelgrass. This may explain why we saw cod congregated into limited areas. The rim area also provides juveniles with shaded cover, due to varying degrees of bio-fouling, from the top, bottom and side. The fish may select
these locations due to perceived risk from predators present around the cage (striped bass, dogfish, harbor and gray seals).

Home range studies of cod in the wild have documented small localized areas of use (Cote et al., 2004; Neat et al., 2006; Espeland et al., 2007). Calculations of volume used in the grow-out net were similar in 2004 and 2006 (Mean = 349.85 ± 84.42 m$^3$), however individuals within the nursery net (Mean = 177.79 ± 25.68 m$^3$) occupied 49.2% less space per individual. While individuals within the nursery net never utilized the full volume of the nursery net (600 m$^3$), the drastic increase in individual volume use when released from the nursery net into the grow-out net gives evidence that movement may have been constricted within the smaller net. Though animals were still limited by the dimensions of the grow-out cage, figure 9 illustrates that the total space use of 13 individuals occupies only ~50% of the total cage volume. This suggests that space use was probably not limited within the larger net at this density. However, there may be limitations on preferential space located around the rim of the cage.

Overall, crowding in small parts of the cage demonstrates inefficient use of the culturing environment, as well as inaccurate estimates of density (kg/m$^3$). While calculations of overall density within the cage may be low, patchy distribution of animals within the culturing environment may result in areas of localized high density, causing the potential of density related stress. A thorough analysis of space use, for different species of cultured fish, would allow researchers and engineers to evaluate and test future cage designs to promote the even distribution of individuals, and full utilization of the culturing environment.
Effects of Operational Stresses

Lights

The results of our study clearly showed elevated swimming speeds during periods of artificial illumination. While photoperiod manipulation has been documented to have positive potential gains to cod grow out through delayed sexual maturation, the results of our behavioral study indicates this technique may provide additional stress, and elevate swimming speeds and energy demands. Increasing swimming speeds from 9.6 cm/s (average night swimming speed), or 17.5 cm/s (average day swimming speed), to 29.1 cm/s increases metabolic oxygen consumption 8.4% daily ($\text{MO}_2=34.8 \times 4.79^U$, Webber et al., 1998). These effects could be significant enough to negate the biomass increases associated with delayed maturation. To minimize the impact of artificial lighting on the cod, a re-evaluation of the technology may mitigate additional stress. The lighting system used in this study was controlled as a simple on-off circuit. Sudden illumination of the cage may cause a startle effect as documented in rainbow trout (Chandroo et al., 1999). Secondly, illumination levels were not previously adjusted to natural ambient lighting conditions. Natural light conditions within the submerged net pen were greatly reduced due to the depth and bio-fouling of the cage. Stress may have been caused by instantaneous and excessive illumination of the cage beyond the natural levels. The use of behavior to evaluate stress should allow researchers and engineers to develop technologies that replicate natural conditions, thereby reducing stress.
Density

The natural increase in density within the nursery net resulted in a change of daily rhythms, characterized by consistent activity throughout the day and night. Increased density has also been shown to alter behavior in rainbow trout (Cooke et al., 2000; Begout Anras and Lagardere, 2004) and turbot (Begout and Lagardere, 1993), and has been attributed to a stress reaction. While swimming speeds during the day showed no significant increase, night swimming speeds increased from 0.27 ± 0.09 BL/s, at low density, to 0.49 ± 0.13 BL/s, at high density. The elevated nocturnal swimming speed almost certainly results in increased metabolic demand, and thus would have energetic consequences that could potentially reduce growth.

Additionally, increased density resulted in changes in swimming behavior from milling to schooling behavior. The initiation of schooling behavior was likely due to decreasing distance between nearest neighbors as density increased, so that fish respond by schooling to reduce the likelihood of collisions with neighboring cohorts (Klarreich, 2006). Our data indicate that fish farmers could control schooling behavior in cod by carefully manipulating the density of fish within the net pen.

Conclusions

Ultrasonic telemetry has proven to be a powerful tool in studying behavior in aquaculture. Results of this study show that captive cod have predictable behaviors and rhythms similar to their wild counterparts. Additionally, we found that operational stresses, such as high stocking density and artificial lighting, cause measurable changes in cod behavior, indicating that behavioral studies could be useful in identifying and minimizing operational stresses. Finally, behavioral studies can provide important
information on the suitability of cage design, leading to increased production efficiency and animal welfare.
CHAPTER 3

FEEDING BEHAVIOR OF ATLANTIC COD, *GADUS MORHUA*, IN AN OFFSHORE AQUACULTURE NET PEN

Abstract

The feeding behavior of Atlantic cod, *Gadus morhua*, in an offshore net pen was assessed using a combination of stomach content analysis and ultrasonic telemetry. Stomach content analysis (N=474) was performed monthly, between fall 2006 and spring 2008, to provide a population level assessment of feeding activity. The majority of the fish sampled (77.6 ± 14.1%) had recently consumed pellets in their stomachs. Unexpectedly, the stomachs of 31.8 ± 26.6% of the cod contained a combination of blue mussels, *Mytilus edulis*, and pellets, and an additional 8.5 ± 10.4% of individuals solely consumed mussels. A 3-D, high resolution, ultrasonic telemetry system was used to document fine-scale movements associated with feeding behavior during September and November of 2004, and October 2006. Telemetry was used to assess individual fish behavior, including daily feeding patterns, preferential feeding areas and duration of feeding. Feeding behavior consisted of movement from the cage perimeter into the center feeding area, with periodic vertical excursions toward the feed source. Aggressive feeding behavior was displayed in 42.7 ± 4.6% of cod daily, while 25.8 ± 3.7% of cod displayed no interest in feeding during a feeding cycle. Additionally, 31.5 ± 4.5% of cod displayed an intermediate feeding behavior, moving into the feeding area but not making
vertical movements toward the feed source. Feeding intensity varied with season, number of feeding cycles and time of day. The combination of stomach content and ultrasonic telemetry data suggests cod display multiple feeding strategies: aggressive, non-aggressive and non-feeding, or scavenging. Multiple feeding strategies may reduce competition within the population. Overall, this study has identified that cod have a distinct and quantifiable feeding behavior. The development of a system that provides biological feedback could aid in assessing current feeding models and optimize future feeding practices.

Introduction

Aquaculture is one of the fastest growing food producing sectors of the world, with an annual compounding growth rate of 8.8% per year since 1970 (FAO, 2006). While aquaculture production continues to increase, it will inevitably be limited by available and affordable feedstock (Powell, 2003). Establishing proper feeding techniques is fundamental to optimizing commercial aquaculture. However, due to the difficulty associated with large scale monitoring (e.g. large volumes, numerous animals, and turbid water conditions; Knights, 1985; Smith et al., 1993; Baras and Lagardere, 1995), especially in offshore net pens, few studies have investigated feeding behavior in the field.

Traditionally, feeding regimes used in the field have been based on information extrapolated from small-scale laboratory experiments. It is unclear, though, how well these translate (Knight, 1985; Juell and Westerberg, 1993, Smith et al., 1993; Juell et al., 1994). For example, Smith et al. (1993) demonstrated that appetite in salmon was
closely correlated with day length in the field, while previous laboratory experiments suggested that appetite was more closely related to temperature. Coordinating feeding with fish appetite under large-scale conditions will improve culturing techniques by minimizing food waste, thus reducing cost and environmental degradation, in addition to optimizing food conversion ratios (FCR) and growth.

While more tools need to be created to effectively assess feeding efficiency, and provide biological feedback relevant to feeding schedules, behavioral studies have documented clear changes in fish behavior associated with feeding (Juell and Westerberg, 1993; Smith et al., 1993; Juell et al., 1994; Clark et al., 1995; Beaumont et al., 2002; Mallekh et al., 2003). Recent studies are using technological developments to provide real-time biological feedback. Using hydroacoustics, salmon were documented to move toward the surface at the onset of feeding, but descended as feeding continued, thus revealing a behavioral indicator of satiation (Juell et al., 1994). In addition, ultrasonic telemetry studies illustrated that individually tracked salmon did not participate in 74.7% of feeding events (Juell and Westerberg, 1993). Mallekh et al. (2003) also monitored an acoustic "feeding" signature in turbot to assess feeding levels. Systems that provide real-time feedback will allow growers to instantaneously adjust feeding regimes to accommodate fish appetite.

Chapter 1 previously described cod feeding behavior in a submerged net pen using ultrasonic telemetry. Cod activity was predominately associated with the bottom surfaces and outer rim of the net pen, except during feeding events. Feeding behavior in cod was described as a vertical ascent from the bottom of the net toward the feeding tube. Feeding excursions were short (~2-3 min), but multiple vertical trips were documented
during a feeding session. Similar behavior has been documented in salmon, where feeding represents a trade-off between the attraction to food and avoidance of the surface (Ferno, 1989; Juell et al., 1994).

The goal of this study was to quantify the feeding behavior of cod in a submerged net pen, and test the hypothesis that all cod in the pen feed each time food is presented. Two techniques were used to assess feeding: stomach content analysis and telemetry. The stomach content analysis provided a population level assessment, indicating what percentage of the fish fed during each feeding session, as well as information about the quantity and quality of food eaten. The drawbacks of this analysis were its inability to assess fluctuations in individual behavior, feeding strategy and feeding history. In contrast, telemetry made it possible to analyze individual fish behavior, including daily feeding patterns, preferential feeding areas, and duration of feeding as well as modifications to behavior related to feeding (i.e. increased swimming speed). Together, these two approaches demonstrated that cod in net pens express a range of feeding behaviors, and supplement their formulated diet with mussels that grow on the net pen.

Materials and Methods

Study Site

The University of New Hampshire’s Open Ocean Aquaculture Project’s (OOA) study site is located 13 kilometers off the coast of New Hampshire and 1.5 kilometers south of the Isle of Shoals. To evaluate the feasibility of commercial offshore aquaculture, 30,000 juvenile Atlantic cod (Gadus morhua) were stocked into a Sea Station 3000 net pen (25 m wide x 15.5 m deep; Net Systems Inc., Bainbridge, WA) in September 2003 and reared until harvest in February 2006. An additional 50,000
juvenile cod were subsequently stocked in April 2006 intended for harvest in summer/fall 2008.

**Telemetry Equipment**

The HTI model 291 ultrasonic telemetry system was selected to obtain positional information from cod due to its 1) small tags, 2) ability to track multiple fish simultaneously in 3 dimensions and 3) its high spatial and temporal resolution. This system has been described in detail in Chapter 1. In brief, four omni-directional hydrophones were attached to the net pen and hardwired to an acoustic receiver on the surface. The receiver and an associated laptop computer were located within an automated feed buoy (described by Chambers and Howell, 2006) in 2004, and part of a multi-system monitoring buoy in 2006.

**Surgical Procedure**

The following technique was previously described and evaluated in Chapter 1. In brief, a group of 6-12 cod were captured by divers at the offshore site, removed from the grow-out net and placed within a decompression cage. The fish were slowly decompressed at a rate of 3 meters every 30 minutes. At the surface fish were placed within a temperature controlled, aerated tank on-board the research vessel. The fish were anesthetized with MS-222 (50 ppm). A small incision was made in the ventral side, posterior to the pectoral fins. An ultrasonic tag was then implanted into the abdominal cavity of the fish and two sutures were used to close the incision. HTI F-tags (9 mm diameter x 21 mm length; 2.2 g in air, 1.2 g in freshwater; duration: ~30 days) were used for smaller cod, and HTI G-tags (11 mm diameter x 25 mm length; 1.9 g in freshwater; duration: ~30-50 days) for larger cod. Tags did not exceed 2.5% of the body weight as
recommended in the literature (Baras and Lagardere, 1995; Brown et al., 1999; Jepsen et al., 2002). The HTI transmitters were programmed at a pulse rate between 1.7-3.3 seconds per location, yielding 866 – 1,770 positional fixes per fish/hour. Sampling intervals over 10 seconds were shown to significantly alter calculations of swimming speed (Chapter 1). Fish remained in the holding tanks onboard until fully recovered from surgery (~ 30 min) and then returned to the net pen. Chapter 1 documented no significant effect of the transmitters on the locomotory or feeding behavior of cod in the laboratory, and no long-term change in behavior of tagged animals in the field.

**Feeding Experiment**

An automated feed buoy, described by Chambers and Howell (2006), controlled the daily delivery of food to the fish. Pellets and water were combined in a mixing chamber, within the feed buoy, and then pumped to the cage 15m below via 6” flexible PVC hose. The feed hose entered the net at the top of the cage slightly off center. This allowed pellets to sink through the entirety of the cage, allowing for maximum retention time, before exiting the bottom of the cage.

In 2004, fish were fed a pelletized 2.5 mm semi-sinking, marine diet (50% protein and 14% lipid; Burris Feed Company, Baton Rouge, LA), once daily, beginning at 1100h. The feed buoy intermittently dosed food into the cage every 90 seconds for the duration of the feeding cycle (~90 minutes). Cod were fed 140 kg/day (1.5% BW/day) though late fall but increased to 160 kg/day in November, to compensate for increased growth.

Due to technical difficulties with the large feed buoy, fish were fed using a smaller feed buoy in 2006. Due to the size and power restrictions of the buoy, powered by wind and solar, fish were fed on sixty minute cycle, twice daily, at 1000 and 1600h, at
1% body weight per day. Feed amount was adjusted monthly to account for growth. Additionally, cod tracked in 2006 had a slightly different life history than individuals in 2004. Cod in 2004 were directed transferred into net pen, while cod in 2006 were stocked into a smaller nursery net (200 m$^3$), located within the larger net pen, to allow for partial grow-out before being released into the outer pen at a larger size (~150 g).

Chapter 1 previously documented a distinct change in swimming behavior during periods of feeding. Typical behavior of cod, within this net pen, consists of the occupation of areas in the net associated with the bottom and outer areas of the net pen. During feeding cycles cod display distinctive movements away from the outer rim into the feeding region (Fig. 3.1). While some animals displayed directed movements towards the feeding tube, other animals remained on the other side of the cage. Additionally, a population of animals displayed movements into the feeding area, but no vertical movement toward the net pen. These animals occupied space lower in the water column (Fig. 3.2).
Fig. 3.1 Movement of a single cod during three hours of the day. Typical behavior consisted of occupation of the bottom and rim area during both day (A) and night (B). During feeding cod made movements into the feeding area (denoted by the square) and vertical movements toward the feed source (denoted by the X).
Fig 3.2: Different feeding strategies exhibited by five cod during a single feeding bout. Cod typically display one of three different behaviors: aggressive feeding (A, B), intermediate feeding (C), or disinterest (D, E). Arrow denotes point of feed entry.
To evaluate feeding behavior, twenty-three cod were tracked during September and November 2004 (N=10; 34.2 ± 4.6 cm) and October 2006 (N=13; 27.8 ± 2.0 cm). Position was logged continuously for the duration of the tag life, which ranged from 9 to 26 days. Positional information was analyzed during feed events to assess whether a fish participated in a feeding session or not. To determine if fish were present around the feeding tube during a feeding event, a 20 x 20 foot feeding area (Fig. 3.1) was delineated around the feeding tube. The feeding area was unrestricted in the depth axis to document movement of cod into the feeding area under the feeding tube at lower depths of the cage. Diver and video observations confirm that feed remained within the feeding area until exiting the bottom of the cage, despite water currents. A visual assessment of the telemetry tracks was subsequently used to determine how many times a fish entered the feeding area, and how many vertical migrations they made within the feeding area. Additionally, swimming speed during feeding was compare with non-feeding day time hours to evaluate if feeding elicited a detectable change in swimming velocity.

Based on these data, feeding participation was subsequently classified into three categories: Participation, No Participation and Undetermined. Participation was based on presence within the feeding area and vertical movements toward the food source. No Participation was determined by a lack of presence within the feeding area during any part of the feeding cycle, denoting no access to feed. Undetermined was classified as presence in the feeding area during a portion of the feeding cycle, but no directed vertical movements within the feeding area. Daily feeding efficiency was calculated based on the number of individuals within each classification compared to the total tracked population.
Visualizations of telemetry tracks were created using Tecplot software (Version 10, Tecplot Inc., Bellevue, WA). Instat was used for all statistical analysis (Graphpad Software, La Jolla, CA). A Kolmogorov-Smirnov test was conducted on all analysis to test for Gaussian distribution. Student’s unpaired T-Test’s were used to compare numbers between experimental trials (i.e. years and feeding times). One-way ANOVA with Tukey-Kramer post test were conducted to test between classification groups. All data is represented as mean ± SEM.

Stomach Content Analysis

Cod were sampled monthly between fall 2006 and spring 2008 (N=474; 16 samplings) to assess feeding efficiency. Immediately following a feeding cycle, as described above, a sample of fish (between 15 and 57) were captured by divers and brought directly to the surface. Stomach contents were analyzed to determine presence and quantity of pellets. Additionally, due to frequent observation, the presence and quantity of blue mussels, *Mytilus edulis*, were recorded.

Results

Stomach Content

Stomach content data revealed that 77.6 ± 14.1% of cod had undigested pellets in their stomach. The stomachs of individual cod contained 7.0 ± 3.4 pellets, but some had as many as 24 pellets. Almost a third of the stomachs (31.8 ± 26.6%) contained a mix of pellets and mussels and 8.5 ± 10.4% of animals had solely mussels (Fig. 3.3). Fish had an average of 3.8 ± 2.3 mussels, but individuals contained as many as 20 mussels. Finally, 13.3 ± 3.5% of individuals had empty stomachs.
Fig 3.3: Classification of cod stomach contents (N=474). Pellets were observed in cod stomachs significantly more than other categories (P<0.05), denoted by asterisks. No significant differences were observed between stomachs with pellets and mussels, mussels or empty (P>0.05).
Telemetry Data

Assessment of feeding was primarily based on the position of the animal during a feeding event, as average and burst swimming speed showed no correlation with feeding behavior. Swimming speed was higher during feeding periods in September 2004 (0.48 ± 0.03 BL/s; 15.6 ± 1.0 cm/s), compared with non-feeding hours (0.38 ± 0.02 BL/s; 12.5 ± 0.6 cm/s; p=0.020), but was not significantly different in November 2004 (Feeding: 0.43 ± 0.02 BL/s; 16.6 ± 0.5 cm/s, Non-feeding: 0.41 ± 0.02 BL/s; 16.3 ± 0.8 cm/s; p=0.651) or 2006 (Feeding: 0.34 ± 0.01 BL/s; 9.6 ± 0.3 cm/s, Non-feeding: 0.35 ± 0.01 BL/s; 9.7 ± 0.4 cm/s; p=0.876). Additionally there was no significant difference in swimming speed between feeding classifications (i.e. participation, no participation and undetermined) (p<0.05).

Feeding was most closely correlated to position within the feeding area. Feeding individuals occupied space within the feeding area for 22.7 ± 1.4 minutes during the presentation of food compared to just 7.8 ± 0.6% of time (4.7± 0.4 minutes/hour) during non-feeding hours (Fig. 3.4). Feeding cod made an average of 14.5 ± 1.0 trips into the feeding area during the feeding cycle compared with 6.3 ± 4.3 when food was not present. In contrast, non-feeding cod spent an average of 1.3 ± 0.3 minutes/hour within the feeding area during feeding, compared with 3.6 ± 0.5 minutes/hour during non-feeding hours. Undetermined individuals averaged 11.9 ± 1.0 minutes/hour during feeding and 7.9 ± 0.7 minutes/hour outside of feeding periods.
Figure 3.4: Analysis of occupation of the feeding area. The proportion of time spent with the feeding area during feeding events and non-feeding hours. Cod displaying active feeding behavior occupied space within the feeding area significantly more than the same individuals during non-feeding hours (P < 0.001). Individuals displaying no participation in feeding, or undetermined activity, showed no significant change in space use within the feeding area (P > 0.05).
When fed once per day in 2004 (N=13), 31.2 ± 5.8 % of cod displayed daily feeding behavior, consisting of vertical migrations up to the feeding tube, while 26.5 ± 6.5 % of individuals did not participate in feeding, and 42.3 ± 7.0% displayed undetermined activity. Analysis of consecutive days of feeding showed that individual behavior was consistent between feeding periods. For example, cod displayed the same feeding strategy to the previous day 57.4 ± 5.3% of the time.

As seasons changed from September (N=6) to November (N=7) aggressive feeding declined from 40.8 ± 6.9% to 22.9 ± 8.1% (p=0.125), no participation events decreased from 34.2 ± 9.7% to 20.0 ± 8.7% (p=0.299), and undetermined feeding events increased from 25.0 ± 7.2% to 57.1 ± 8.1 % (p=0.022) (Fig. 3.5). Statistical analysis documented no significant difference between categories in September (p=0.397), however, a significant difference was documented between the undetermined group and participation, and no participation groups, (p=0.009) in November.

In 2006, when fed twice per day (N=14), 53.5 ± 5.8% of cod participated in feeding, 25.1 ± 3.9% of cod showed no interest in feeding, and 21.4 ± 4.4% were categorized as undetermined. While not significantly different, a trend showed feeding differed slightly between morning (N=7) and afternoon session (N=7), showing increased feeding in the afternoon (60.1 ± 8.5% vs. 46.9 ± 7.6% respectively; p=0.270). The increase in the number of individuals feeding in the afternoon, compared with the morning, resulted in a reduced number of individuals not participating (Afternoon: 23.4 ± 4.7% vs. Morning: 26.7 ± 6.4%; p=0.690) and undetermined (Afternoon: 16.5 ± 5.5% vs. Morning: 26.4 ± 6.8%; p=0.276) (Fig. 3.6). Statistical analyses between groups documented a significant difference between feeding and non-feeding individuals as well.
as undetermined groups (p<0.001). However, no difference was shown between the two latter groups (p>0.05).
Fig. 3.5 – Seasonal variations in feeding motivation. A trend in cod behavior, while not statistically significant, displayed a decreased tendency towards participation ($p=0.125$) and no participation ($p=0.299$) feeding behavior in November, compared with September, while individuals had a stronger tendency towards undetermined behavior ($p=0.022$). Asterisk denotes significant difference within classification groups.
Fig. 3.6 – Temporal variations in feeding behavior. While not significant, individuals displayed a slightly stronger affinity toward feeding in the afternoon, compared to morning (p=0.270). Afternoon feeding simultaneously displayed lower incidences of non-feeding (p=0.690) and undetermined feeding (p=0.276).
Unlike 2004, individual cod showed all three feeding traits within the experimental trial, however they’re participation in feeding appeared to be random. Cod seldom displayed vertical migrations; instead they remained lower in the net pen (Fig. 3.7). This behavior could indicate that cod waited for food to sink.

Feeding behavior displayed some variation between years (Fig. 3.8). While non-feeding behavior remained fairly consistent (p=0.844), there appeared to be a trade-off between participation and undetermined events. Participation events were significant higher (p=0.011) in 2006, whereas undetermined events were significant higher in 2004 (p=0.017).
Fig. 3.7 – Alternative feeding strategies in cod. In contrast to individuals in 2004, cod in 2006 documented tight occupation of lower regions of the feeding area displaying no vertical movement toward the feeding tube. This indicates that cod were waiting and feeding on pellets as they sunk lower into the net pen.
Fig. 3.8: Yearly variation in feeding behavior. While no participation events remained consistent (p=0.844), yearly differences were noticed between participation (p=0.011) and undetermined groups (p=0.017), with stronger feeding activity documented in 2006 compared with 2004. Asterisks denote significant differences within classification groups.
Discussion

The information acquired from the combination of stomach analysis and telemetry data provided a holistic view of feeding behavior unattainable by an individual technique. The stomach analysis data documented that 77% of cod were actively feeding. This is in contrast to the behavioral data which showed that 23-53% of cod exhibited aggressive feeding behavior. While aggressive and non-feeding individuals’ behaviors were distinctly different behaviors, 21-42% of cod displayed an intermediate, “undetermined” behavior. The combined proportion of aggressive (~42%) and intermediate feeding (~32%) events closely matches the number of actively feeding individuals from the stomach analysis data (~77%). This suggests that fish displaying the intermediate feeding behavior were probably feeding individuals. Thus cod may have two distinct feeding strategies: aggressive and non-aggressive.

The remaining 23% of individuals were reported as non-feeding animals. Whether these individual frequently skipped meals, accounting for the “runt” phenomenon, ate during other feeding events, or solely consumed mussels remains unclear. The telemetry data shows that individuals frequently skip meals, however all individuals tracked within this study documented some form of feeding during the study period. Additionally, stomach content analysis provides only a snapshot of one moment in time. Though it is unclear the long term dynamic of individual feeding behavior, this data suggests that on any given feeding event 23% of individual do not feed. Information of this nature will prove important in fine-tuning daily feeding regime and indicate that a combination of large- and small-scale studies are required to adequately assess feeding behavior.
Selection of alternative feeding strategies may reduce potential competition (Juell and Westerberg, 1993). Cod in 2004 displayed individual preferences to feeding strategies, with individuals consistently displaying consecutive aggressive or non-aggressive feeding behaviors. Cod have displayed hierarchical aggressive feeding behavior in the lab directed toward smaller conspecifics (Bjornsson, 1993). While this research may indicate the presence of more aggressive individuals, all individuals tagged within this study were of similar body size, weight and condition. In 2006, individuals fluctuated between all three strategies. This may indicate differing daily levels of hunger; however the daily variation in feeding strategy appeared to be random.

Stomach content analysis documented that three-quarters of fish had recently fed when caught, while only 13% of individuals had empty stomachs. This indicates fairly uniform distribution of food among individuals. Fish consumed, on average, seven pellets. Unexpectedly, 41.1 ± 7.4% of fish had recently consumed blue mussels, *Mytilus edulis*, with 8% of cod whose stomach content being solely mussels.

While mussels are the primary fouling organism on this net pen (Greene and Grizzle, 2006), all the fouling is on the outside of the net, indicating that cod may consume fouling organisms growing on the inside of the net (Pers. Obs.). Blue mussels are common prey of wild juvenile cod (Hussy et al., 1997), so it is not unexpected that farm raised cod would feed on those fouling the net pen. The consumption of alternative food could potentially indicate: 1) under-feeding, or 2) preference of wild food to commercial feed pellets. Alternatively, it may be a by-product of net biting, including areas that display structural difference to the background netting, common among farmed cod (Moe et al., 2007).
Clark et al. (1995) documented that cod had a preference of capelin over two commercial fish pellets, including frequent rejections of the fish pellets. Despite the reasoning for the consumption of the mussels, this provides a major food supplementation to the farm stock, and should possibly be included in feeding strategies developed by farm managers.

Feeding behavior was shown to change between September and November, with a shift from aggressive feeding to non-aggressive feeding. This may be due to decreased water temperature, reducing basal metabolism (Brett and Groves, 1979; Jobling, 1988; Claireaux et al., 1995; Claireaux et al., 2000). However, during November cod were artificially maintained at a 12:12 hour photoperiod using underwater lights (Chambers and Howell, 2006). Rillahan et al. (In Prep.) previously illustrated a stress response in these cod. It is unclear whether this would simultaneously change the behavior of feeding fish.

In 2006, cod displayed an alternate feeding strategy whereby individuals rarely made vertical movements toward the feeding tube, instead remaining fixed below the feeding tube. Decreasing water temperatures in October may have limited feeding aggression. Clark et al. (1995) noted cod that were fed in warmer months made frequent trips to the surface for pellets, but remained lower in the water column and waited for pellets to sink in the colder fall and winter months. This alternative feeding strategy may also be explained by different life histories. Cod in 2004, were directly transferred from the hatchery to the grow-out net. In 2006, juvenile cod were placed within a smaller nursery net, located in the center of the grow-out net. The reduced size of the nursery net
restricted vertical movements of cod during feeding. When released from the nursery net, the cod displayed similar feeding behavior within the larger grow-out net.

Within this study, we have proven that cod have distinct and quantifiable feeding behaviors. Data obtained from the non-lethal telemetry system closely matches that of the larger scale stomach content analysis; however this system lacks the ability to provide a rapid assessment of large numbers of individuals. While positional telemetry has many benefits, there is still a need for a system to directly monitor food consumption, retention and quantity of consumed food.

Further research needs to be conducted to determine how seasonal variation, environmental variables, feeding regime, feeding rate and diet affect feeding dynamic. However, understanding feeding behaviors in farmed fish can provide real-time information to growers allowing for fine-tune adjustments of feeding schedules and feed loads. Increased feeding efficiency will reduce waste, thereby reducing cost and pollution as well as increasing animal well-being, growth and profit.
CONCLUSIONS

The video/telemetry system we designed, built and utilized proved to be ideal for studying fish in an offshore net pen. Video data provided information about the behavior of the population as a whole, while telemetry data made it possible to quantify the movements of individual fish, both during the day and during the night. The particular telemetry system used, manufactured by HTI, was ideal for this application because of the high resolution, rapid sampling rate, small transmitters and ability to plot positions in three dimensions. Both laboratory and field studies demonstrated that implantation of transmitters had no impact on the swimming or feeding activities of cod. Signal retention was 84.9 ± 6.0%, resulting in 1283.4 ± 252.5 locations per hour. While we were obtaining fixes every 2-3 seconds, our simulation indicated that, with cod, we could reduce the sampling rate to 10 second intervals. However, at sampling rates slower than this, there would be a significant underestimation of distance traveled.

Cod behavior appeared to be independent of conspecifics, consisting of primarily "milling" behavior, rather than schooling. Individuals exhibited clear diurnal rhythms with higher swimming speeds during daylight hours (17.83 ± 5.5 cm/s; 0.57 ± 0.18 BL/s) compared to night hours (6.57 ± 0.53 cm/s; 0.2 ± 0.03 BL/s). Cod spent 95.7-99.36% of their time swimming less than 1 BL/s; however they exhibited burst swimming at speeds of up to 186.98 cm/s (5.84 BL/s). Daily rhythms and swimming speed were influenced by both artificial lights and stocking density. Periods of artificial illumination increased cod activity during the day by 66.4% and at night by 202.6%. Increasing stocking
density resulted in the deterioration of daily rhythms and the establishment of schooling behavior. Finally, the analysis of cage utilization documented inefficient use of the net pen; with individual space use limited to small overlapping areas within the bottom half of the net pen.

A distinct feeding behavior was documented consisting of movements from the cage perimeter into the center feeding area, with periodic vertical excursions toward the feed source. While only $42.7 \pm 4.6\%$ of cod displayed this aggressive feeding behavior daily, stomach content analysis showed that $77.6 \pm 14.1\%$ of cod had recently consumed pellets. Unexpectedly, the stomachs of $31.8 \pm 26.6\%$ of the cod contained a combination of blue mussels, *Mytilus edulis*, and pellets, and an additional $8.5 \pm 10.4\%$ of individuals solely consumed mussels. The combination of stomach content and ultrasonic telemetry data results suggests cod displayed three feeding strategies: aggressive, non-aggressive and non-feeding, or scavenging. Feeding behavior displayed variations in intensity based on season, number of feeding cycles and time of day.

Although behavioral studies have been limited in full-scale aquaculture operations, it is hoped that the evolution of new technologies, such as those described in this thesis, will enable researchers to gather real-time information about fish welfare. The finding within this study have documented the potential benefit to the development of fish rearing technologies relevant to feeding behavior, activity patterns, density effects, cage utilization and design, as well as the effects of various operational and environmental parameters. Understanding the dynamics of fish behavior will aid in animal rearing by minimizing stress, increasing animal well-being and optimizing production.
FUTURE STUDIES

The development of this system for studying high resolution behavior of individuals has opened a window to understanding animal behavior on a level previously unavailable. While this study focused primarily on Atlantic cod in an offshore net pen, this system can easily be stripped down of its infrastructure (i.e. buoy and power system) to be used in a variety of new environments. Due to the preliminary nature of this study, many additional research questions remain to be answered.

Chapter 1 of this thesis focused on the technical evaluation of this system. Additional research questions include:

- How does the scope of sampling error change with different fish species, cage size and dimensions, and swimming strategy?
- Do fish have the capacity to hear the transmitters?

Chapter 2 highlighted general cod behavior in addition to changes in behavior due to operational stresses. Future studies should investigate:

- Seasonal changes in daily rhythms and behavior.
- Where, when and why burst swimming occurs.
- New cage designs for cod to optimize space use.
- Re-engineering of lighting system to alleviate stress reactions in cod.

Future systems may coordinate with nature light intensity and simulation of natural sunset and sunrise.
- Cost-benefit analysis of artificial illumination if stress cannot be reduced.
- Additional studies need to be conducted on optimal densities as well as
effects of long term effects of density-related stress.
- How various factors affect the underlying energetics, and therefore
growth, of the cod?

The final chapter of this thesis focused on a description of feeding behavior in
cultured cod. Additional work should focus on:
- How does operational or environmental stress affect feeding?
- Evidence for feeding anticipatory activity and/or post-feeding satiation?
- How does feeding efficiency change with different feeding times, time of
day or multiple feeding sessions?
- Are there daily or seasonal fluctuations in feeding?
- Different size cod should be studied to evaluate the social dynamics of
feeding.
- New feeding transmitters need to be constructed in an attempt to evaluate
when and where cod are feeding within, or on, the net pen.
- How does the stomach analysis data change over time? Are mussel
feeders consistently feeding on mussels and pellet feeder consistently
feeding on pellets, or are there daily fluctuations in this behavior?
- Stomach analysis data should be analyzed in relation to morphological
variable to assess how feeding strategy effects growth.
LITERATURE CITED


http://aquaculture.noaa.gov/pdf/06_who1e07act.pdf


http://ocean.ceq.gov/actionplan.pdf

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18-Dec-2006

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IACUC #: 061202
Project: Offshore Production of Cod, Haddock and Halibut
Category: C
Approval Date: 14-Dec-2006

The Institutional Animal Care and Use Committee (IACUC) reviewed and approved the protocol submitted for this study under Category C on Page 5 of the Application for Review of Vertebrate Animal Use in Research or Instruction - the research potentially involves minor short-term pain, discomfort or distress which will be treated with appropriate anesthetics/analgesics or other assessments. The IACUC made the following comment(s) on this protocol:

1. The Committee removed "Abnormal resting postures" in Section V, C.
2. In Section VI, D, v and vi, the Committee adjusted the numbers to correspond with those in Section V, Table 1.
3. The Committee wondered if the transmitter is too large to be installed using a trochar.

Approval is granted for a period of three years from the approval date above. Continued approval throughout the three year period is contingent upon completion of annual reports on the use of animals. At the end of the three year approval period you may submit a new application and request for extension to continue this project. Requests for extension must be filed prior to the expiration of the original approval.

Please Note:
1. All cage, pen, or other animal identification records must include your IACUC # listed above.
2. Use of animals in research and instruction is approved contingent upon participation in the UNH Occupational Health Program for persons handling animals. Participation is mandatory for all principal investigators and their affiliated personnel, employees of the University and students alike. A Medical History Questionnaire accompanies this approval; please copy and distribute to all listed project staff who have not completed this form already. Completed questionnaires should be sent to Dr. Gladi Porsche, UNH Health Services.

If you have any questions, please contact either Roger Wells at 862-2726 or Julie Simpson at 862-2003.

For the IACUC,

Jessica A. Bolker, Ph.D.
Chair

cc: File