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Strategies for Quantifying Sublethal Effects of Marine Catch-and-Release Angling: Insights from Novel Freshwater Applications

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Abstract.—Traditional approaches for assessing the effects of catch-and-release angling have focused either on hooking injury, mortality associated with different handling and environmental conditions, or biochemical indicators of short-term stress response and recovery. These methodologies do not permit the collection of real-time data on the sub-lethal effects and recovery period associated with the angling event, nor do they provide information on long-term fitness impacts to angled individuals. The advent of hard-wired, archival, and telemetered technologies capable of collecting information on fish location, locomotory activity, cardiac function, and various environmental parameters provides researchers with powerful methodologies for monitoring the response of individual fish to different stressors. These technologies and approaches have been used primarily with freshwater fishes, but they may be applicable to marine environments. Compared with freshwater systems, there are unquestionably some additional challenges due to unique characteristics of the marine habitat (e.g., depth, vastness, salinity) and behaviors of marine fishes (e.g., migratory patterns). Irrespective of the challenges, fisheries scientists must begin to look beyond hooking mortality as an endpoint for assessing the success of a catch-and-release angling program. Studies need to be conducted that provide real-time information on sublethal physiological effects, disruptions in behavior, and long-term impacts on the fitness (lifetime reproductive success) of released fish. Despite the fact that managers are usually concerned with population level effects, additional individual-level comprehensive studies are required before we can attempt to understand if and how catch-and-release angling affects populations.

Introduction

Recreational anglers increasingly are participating in nonconsumptive fishing (i.e., catch-and-release angling or some form of selective harvest; Quinn 1996). One reason this change in angler behavior has arisen is in response to the overharvesting of fisheries. Today, a combination of voluntary (Quinn 1989) and mandated (Redmond 1986) catch-and-release programs exists (Barnhart and Roelofs 1977, 1989). Although most fisheries managers are concerned with population, community, and ecosystem level implications of catch-and-release angling, it is the effects of this practice on the individual organism that will culminate in changes at these higher levels of organization.

The possible consequences of catch-and-release angling range from no measurable impact to death. The majority of studies assessing the effects of catch-and-release angling have focused on two areas. The first is assessment of the degree of physical injury incurred by angled individuals coupled with the quantification of immediate or delayed mortality. The second is assessment of the short-term (hours or days) physiological or behavioral responses of individuals that do not die. Although research conducted in laboratories is helping us to understand why fish may die after severe exercise and handling (Wood et al. 1983), we still know relatively little about the physiology and behavior of free-swimming fish following release.

Fish respond to stress with a series of defense mechanisms that are energetically demanding (Barton and Iwama 1991). These defense mechanisms are difficult to identify, but certainly act to impair various physiological processes and likely cause altered behaviors (Heath 1990) that may make an organism susceptible to predation or induce hyperactivity, causing an unnecessary expenditure of energy (Black 1958). Broom and Johnson (1993) have postulated that stress also reduces individual fitness through a reduction in reproductive capability. Tests of that hypothesis, however, have not been forthcoming because measuring the fitness of an individual or groups of individuals over its/their lifetime is difficult as is identifying the stressor that has altered fitness. Many hooking mortality studies have documented high survival rates for fish that were angled and released (Muoneke and Childress 1994). Very few studies, however, have monitored the physiological disturbance associated with angling and handling and the subsequent recovery of free-swimming fish following release. Although high survival rates are fundamental to the goals of nonconsumptive fishing, an equally important goal is to minimize sublethal effects that may decrease fitness. For example, catch-and-release angling practices could disrupt reproductive activities, thereby impacting a population in several potential ways. Year-class strength could be decreased directly in response to a reduction in successful reproduction. Additionally, differential susceptibility of one sex or certain size classes of individuals could alter a population's reproductive characteristics by selectively disrupting the reproduction of those individuals. The opportunity for these impacts clearly is present, but the extent of their occurrence is unknown.

Herein, we review techniques that have been used successfully to obtain information on the sublethal effects of catch-and-release angling in freshwater fishes and assess their relevance and application to marine systems. We also highlight a series of novel and underutilized procedures for monitoring the disturbances associated with angling and discuss how these tools may help us to understand the recovery patterns and energetic costs associated with catch-and-release angling. In addition, we describe a set of desirable characteristics that we feel should be embodied in the "ideal" measure of the response of fish to angling. In particular, we emphasize the importance of measuring more than mortality and encourage scientists to consider sublethal effects, including the assessment of long-term impacts on fitness.

Assessing the Impacts of Catch-and-Release Angling

As the practice of catch-and-release angling has grown, so has the number of studies addressing the effects of that practice. Those studies range from being purely observational to being quite experimental in their approach. The following brief review of different methods for studying the impacts of catch-and-release angling highlights the basic principles behind those methods and provides some key supporting references.

Traditional Approaches

Hooking Injury and Mortality: Studies of physical injury and mortality related to angling are common (Muoneke and Childress 1994) and can be conducted by using mark–recapture techniques or by holding fish in artificial or natural environments, including cages (Matlock et al. 1993), pens (Schisler and Bergersen 1996), or on tethers (Loftus et al. 1988). Physical injury usually involves documenting the location and degree of tissue damage, which is typically a subjective classification (e.g., mild versus extreme). Hooking depth measurements adjusted proportionately to the length of the fish are also common (Dunmall et al. 2001). In one creative study, researchers examined the ocular lenses of fish held in live wells to determine rates of eye injury from handling (McLaughlin et al. 1997). Such unique approaches may be necessary to understand completely the scope of potential injuries that may be encountered during angling and subsequent handling.

Hooking mortality is usually defined as the fraction of fish that do not survive beyond a predetermined recovery period. There is, however, always the potential for the additional stress from holding the fish to bias hooking mortality estimates (Wright 1970). External marking programs have been used to assess hooking mortality (Jagielo 1999), particularly in marine environments; however, the biases associated with tagging mortality, tag loss, and poor tag recovery can confound results and conclusions (Candy et al. 1996).

Muscle and Blood Biochemistry: Biochemical studies can provide important information on the magnitude and duration of physiological disturbance associated with catch-and-release angling practices (Wydoski et al. 1976; Beggs et al. 1980; Gustaveson et al. 1991; Tufts et al. 1991). The high intensity anaerobic exercise experienced during exhaustive exercise accompanying angling (Wood et al. 1983) induces a variety of metabolic disturbances. These include glycogen depletion, alterations in the levels of adenosine triphosphate and phosphocreatine, and the accumulation of end products of anaerobic metabolism, such as lactate and H + protons (Driedzic and Hochachka 1978; Milligan and Wood 1986; Kieffer 2000). These physiological disturbances induce metabolic and respiratory blood acidoses that result in further ionic imbalance, as well as elevated cardiac output (Wood 1991). Hematological studies can be limited by the finite volume of blood that may be sampled without causing additional physiological disturbances. Furthermore, cannulation can result in a secondary stress response (e.g., Gamperal et al. 1994; Mazik et al. 1994). In addition, many experimental designs require that fish be sacrificed, resulting in the collection of samples from different individuals, thus reducing resolution and introducing additional sources of variation.

Studies have also assessed the physiological disturbance to white skeletal muscle (See Kieffer 2000 for review). White muscle is used extensively during the bouts of anaerobic burst swimming that accompany angling (Ferguson et al. 1993; Booth et al. 1995; Kieffer et al. 1995). Similar to hematological studies, these tissue analyses can provide information on the magnitude of physiological disturbance and the duration of recovery. White muscle acid–base and metabolite status (primarily muscle lactate, muscle pH, and metabolic protons) are often used as indicators of stress. A major drawback to most studies involving white muscle analyses is the level of invasiveness required; they almost always require terminal sampling.

Recent developments in nuclear magnetic resonance (NMR) imaging, including NMR spectroscopy (NMRS), permit the noninvasive and nondestructive measurement of the chemical compounds in intact tissues such as phosphorous compounds that fluctuate during exercise, indicating tissue energy status (Van Den Thillart and Van Waarde 1996). These techniques are particularly promising because they allow for the analysis of individual metabolic pathways. To date, studies using this technology have focused on purely physiological questions. This technology, however, could provide future insights into the physiological response of fish to catch-and-release angling stressors. In particular, NMRS may also provide new insights into the effects of air exposure on tissue-level metabolism and oxygen status.

Remote Approaches to the Observation of Behavior and Physiology

A common problem for many behavioral and physiological studies is collecting measurements on free-ranging organisms, including fish (Beamish 1978; Scherer 1992). That kind of information would be particularly useful for assessing the effects of catch-and-release angling. Advances in telemetry now permit the measurement of the behavior and physiology of free-swimming fishes, including activity, metabolic rate, body temperature, heart rate, etc., (Butler 1989), as well as a variety of environmental parameters, including external water or air temperature, light, depth, water conductivity, or some other indicator of habitat characteristics.

Recent advances in the miniaturization of telemetry devices has permitted the development of systems capable of relaying information on location, behavior, and physiology of many more species of fish without disrupting their behavior or physiology (Lucas et al. 1993; Winter 1996). This technology assumes that the transmitter or the attachment procedure does not affect the fish, an assumption that needs to be tested. As technology changes, we will undoubtedly be able to monitor more physiological and behavioral parameters remotely in free-swimming fish (Stasko and Pincock 1977; Baras 1991).

Locational Telemetry

Since 1957, conventional locational telemetry has been used to study the free-swimming behavior of numerous species (Baras 1991; Lucas and Baras 2000), but only in several recent accounts has this technology been applied to studies on catch-and-release angling. Locational telemetry involves attaching a radio or ultrasonic transmitter and then locating the fish using a manual tracking system or a fixed antenna or hydrophone array. The most common application of telemetry to catch-and-release angling has been to examine the postrelease behavior of fish displaced from where they were caught. This activity commonly occurs in competitive angling events (Ridgway and Shuter 1996; Stang et al. 1996). Usually, the objective of these studies is to assess the dispersal rates and homing tendencies of released fish to ensure that tournament release procedures do not create regions of locally high abundance. Several other telemetric studies have used the mobility of fish after release as an indication that they survived the catch-and-release angling event (Jolley and Irby 1979; Walker and Walker 1991; Bendock and Alexandersdottir 1993; Skomal and Chase 1997; Edwards 1998; Makinen et al. 2000; Whoriskey et al. 2000). In these studies, the postrelease behavior and survivorship was assessed for a period of up to several days or until the fish could no longer be located.

Environmental Telemetry

In some cases, temperature-sensitive transmitters have been used to assess behavior and mortality of postrelease fish (Bettoli and Osborne 1998). When fish exhibited negligible movement, and when water temperature data indicated consistently low temperatures indicative of resting on the bottom, the fish were determined to be dead (Bettoli and Osborne 1998). Other researchers have used pressure-sensitive depth tags to examine fish behavior and survival relative to thermal and oxygen stratification following hooking and release (Lee and Bergersen 1996). Perhaps the biggest limitation for all of these techniques is the difficulty in obtaining information on control specimens. The effect of tagging usually cannot be separated from the effect of being hooked and released (Bettoli and Osborne 1998). As such, these studies become more observational than experimental. These studies can also become logistically difficult when dealing with species that are highly mobile; concentrated tracking efforts extending around the clock are often required to obtain sufficient data.

Activity Telemetry

Activity telemetry is used to assess the locomotory activity of fish on a finer scale than is possible with locational telemetry. Changes in activity levels of fish have recently been observed to be sensitive indicators of stress (Schreck 1990; Scherer 1992; Schreck et al. 1997). Oxygen consumption estimates, however, obtained from activity transmitters that have been calibrated in respirometers have only limited utility in studies of catch-and-release angling. Following release, many fish may remain motionless while the oxygen debt is repaid (Gaesser and Brooks 1984; Scarabello et al. 1991). Oxygen consumption estimates based upon activity signals would suggest that the metabolic rate is depressed, when, in fact, it is elevated. For this reason, Anderson et al. (1998) concluded that activity telemetry has limited utility for studies of catch-and-release angling. This technology, however, could be useful for monitoring catch-and-release impacts where locomotory activity displayed by fish is particularly relevant to the life history of a species (e.g., migrations, parental care, ram-obligate ventilators). To date, only one catch-and-release study has been conducted using this technology (Cooke et al. 2000).

Electromyograms (EMGs) are records of bioelectric potentials that are strongly correlated with the strength and duration of muscle contraction. Radio EMG transmitters are commercially available (Electromyogram, EMG, Lotek Engineering Inc., Newmarket, Ontario)[1] and are capable of detecting the fine-scale activity patterns of fish. Electrodes implanted in the axial swimming musculature detect muscle activity and emit signals when a predetermined threshold has been achieved (these are not "raw" electromyograms) (Kaseloo et al. 1992; Beddow and McKinley 1999). Cooke et al. (2000) used

1. Use of trade names does not imply endorsement by the agencies and organizations that we represent.

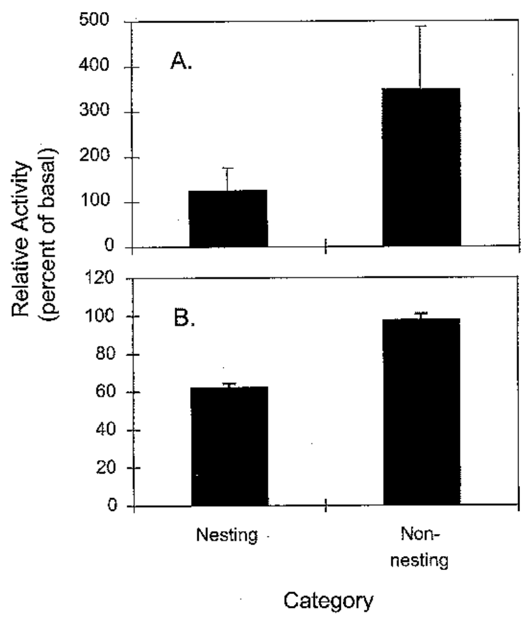

Figure 1. (A.) Locomotory activity of nesting (N = 4) and non-nesting (N = 2) male largemouth bass during 150 seconds of angling. The bars represent the mean (± 1 SE) locomotory activity during the angling period. (B.) Example of locomotory activity of nesting (N = 4) and non-nesting (N = 2) male largemouth bass following 150 seconds of angling. The bars represent the mean (± 1 SE) activity levels for the 24 hour period following angling. Data from Cooke et al. (2000).

EMG transmitters to assess the effects of catch-and-release angling on nest guarding male largemouth bass *Micropterus salmoides* during the parental care phase. These fish, implanted with transmitters, were held in experimental ponds prior to spawning. During angling nest guarding fish fought with lower intensity and when released they had impaired locomotory activity for up to 24 hours (Figure 1A, 1B). Although preliminary and limited to a short battery life, an acoustic transmitter that collects information on "raw" muscle EMG's also has been described recently (Dewar et al. 1999).

Early attempts to measure tail-beat frequency using radio telemetry (Ross et al. 1981; Johnstone et al. 1992) were apparently successful, but they have not become readily available in the commercial market and have not been applied to catch-and-release angling. The first attempt to correlate tail-beat frequency to ultrasonic telemetry signals was based on variations in continuous wave signals resulting from the undulations of body and tail (Doppler effect; Stasko and Horrall 1976). This approach has not been widely adopted. Two more recent developments, both of which are ultrasonic and thus applicable to marine environments, may be applicable to catch-and-release angling. The first is a tail-beat transmitter that emits a signal with every lateral tail-beat (Lowe et al. 1998). The second is a device that utilizes a pressure differential sensor capable of estimating energy output though the frequency and amplitude of tail-beats (Fred Voegli and Dale Webber, Vemco Inc., personal communication). These devices are less invasive than current EMG technologies.

Some researchers have attached speed-sensing transmitters to fish. Block et al. (1992) attached acoustic transmitters that relayed information on depth, water temperature and speed of blue marlin *Makaira nigricans*, as they were tracked for 25–120 hours. Speed was measured by a velocity meter equipped with a plastic propeller containing a magnet that activated a reed switch that was trailed from a semirigid stock attached to the transmitter. A paddle-wheel style acoustic activity transmitter was deployed by Sundström and Gruber (1998) on elasmobranchs. This device can be affixed quickly and calibrated in a respirometer, but occasionally the paddle wheel becomes stuck (this is a problem with all paddle wheels and propellers). In addition, speed-sensing devices may overestimate swimming speed and energy expenditure due to fish gliding and may also be influenced by water-current speed and direction (Brill et al. 1993).

Ventilatory Telemetry

Telemetry studies quantifying ventilatory/opercular rates have been sparse in the literature. Although this technology was developed more than 25 years ago, it has not become a well-used approach. The few studies that have been published do not investigate catch-and-release angling (Oswald 1978; Rogers and Weatherley 1983; Rogers et al. 1984).

Heart Rate Telemetry

Heart rate (HR) telemetry devices have taken several forms, all of which have electrodes placed in or adjacent to the pericardial cavity to detect electrical activity indicative of heartbeats. Heart rate telemetry has been used to assess the metabolic rate of free-swimming freshwater (Priede and Tytler 1977; Priede 1983; Armstrong et al. 1989; Lucas 1994) and marine fish (Priede and Tytler 1977; Scharold and Gruber 1991). Although success has varied (Thorarensen et al. 1996), at present, this may be one of the best ways to monitor postexercise physiological activity remotely, although it may not be suitable for all species (Anderson et al. 1998). Anderson et al. (1998) used prototype HR radio transmitters (Lotek Engineering) to monitor recovery of free-swimming Atlantic salmon *Salmo salar*. Following angling at various temperatures, HR only increased 15–30% above resting levels. The problem with using HR as an indicator of metabolic rate is that the majority of fish species increase cardiac output (CO) principally through an increase in stroke volume (SV) rather than HR (Farrell 1991; Farrell and Jones 1992; Thorarensen et al. 1996). For species that are frequency modulators (e.g., tuna, Brill and Bushnell 1991; Farrell 1991; smallmouth bass, *Micropterus dolomieu*, Schreer et al. 2001a), heart rate transmitters can provide reliable data, but for the majority of other species examined to date, (Farrell 1991), a more reliable correlate of oxygen consumption requires the measurement of CO, which is a function of both HR and SV (Thorarensen et al. 1996).

Cardiac Output

The measurement of CO addresses many of the shortcomings of activity transmitters and HR telemetry. Measuring locomotory muscle activity can be useful to determine if exposure to environmental factors modifies the activity level of the fish. Measuring that activity, however, will not allow detection of changes in metabolism associated with maintenance of homeostasis or recovery from oxygen debt following periods of increased activity. Heart function is influenced by variations in metabolism from all sources because oxygen consumption is a function of CO and the amount of oxygen that is extracted from the blood as it passes through tissues (EO_2). As mentioned above, HR may not always be a reliable correlate of oxygen consumption, and therefore, monitoring CO, which also yields HR and SV, is important.

Several techniques have been used to measure CO in fish, including indirect (Fick equation) and direct (cuff-type or cannulating electromagnetic or Doppler flow probes) methods (Farrell and Jones 1992). In our work, we use cuff-type ultrasonic Doppler flow probes that are inserted around the ventral aorta and hard-wired to a flowmeter (e.g., Cooke et al. 2001; Schreer et al. 2001a). The Doppler flow probe uses a crystal transducer to emit a pulsed sonic signal. Due to Doppler shift, when the signal is reflected from a moving object in the blood (i.e., a red blood cell), a shift in the signal frequency is observed. This represents a velocity and is measured as a change in voltage. Peaks in voltage/velocity represent a heartbeat, and counting peaks per unit time yields HR. The mean voltage per unit time is an index of CO (absolute flow can be calculated in volume/time–1 via a postmortem calibration). Dividing CO by HR yields SV.

Although monitoring the CO of fish provides the most rigorous information regarding the metabolic response and recovery to angling, there are several limitations. First, there are currently no remote blood flow telemetry devices; all require a hard-wire for signal collection. As a result, all studies using CO must be conducted under confined laboratory or semiconstricted conditions. Several laboratories and companies are currently working on this problem, and it is expected that a telemetric version will be available in the near future. Second, CO and its components, HR and SV, provide only two of the three parameters necessary for calculating oxygen consumption, the third being EO_2. Changes in EO_2 may have a considerable effect on metabolic rate, especially in exercising fish. Two studies have assessed the cardiac disturbance associated with catch-and-release angling (Cooke et al. 2001; Schreer et al. 2001a). The first swam smallmouth bass in a respirometer at speeds that elicited burst responses similar to those observed during angling. Cardiac disturbance was influenced by both degree of exhaustion and water temperature, with time to recovery generally increasing with both parameters (Schreer et al. 2001a). In a second experiment, cardiac output was used to assess the effects of air exposure duration on recovery in rock bass *Ambloplites rupestris*. Long exposures (180 s) resulted in cardiac recovery periods lasting more than twice as long as short (30 s) exposures (Cooke et al. 2001). Examples of data generated from this approach are included as Figures 2 and 3, the effects of air exposure on sea-ranched Atlantic salmon and the effects of handling on Arctic char *Salvelinus alpinus*. Using this approach, it is possible to quantify the degree of cardiac disturbance and the duration required for cardiac parameters to normalize. Additional work is required to establish how different cardiac parameters correlate with levels of biochemical disturbance.

Long-Term Impacts

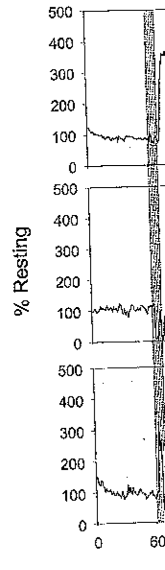

Figure 2. Examp exposure in a (male, 1.320 kg, water at 5°C. Fi round tank and e ues are percent r minute air expos returned to the w

Reproductive

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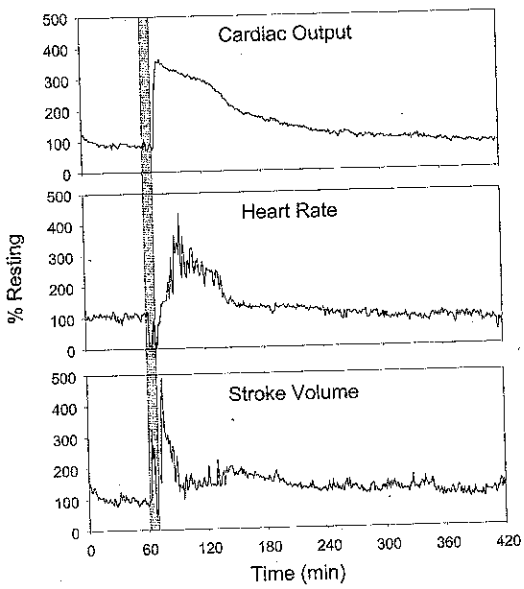

Figure 2. Example of cardiac response to 10 minute air exposure in a Norwegian sea-ranched Atlantic salmon (male, 1.320 kg, 605-mm total length) acclimated to fresh water at 5°C. Fish was removed from a 0.28 m^2 × 0.36 m round tank and exposed to air using a wetted sling. All values are percent resting with resting equal to 100%. The 10 minute air exposure (shaded area) ended when the fish was returned to the water.

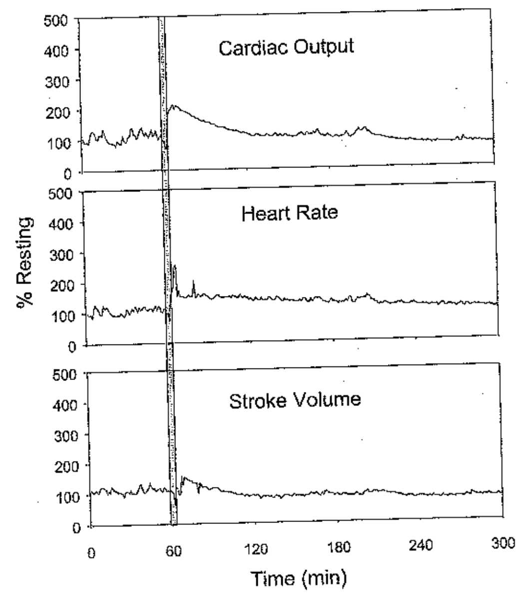

Figure 3. Example of cardiac response to manual disturbance and physical handling in an Arctic char (male, 1.223 kg, 455-mm total length) acclimated to fresh water at 5°C. Chasing fish, which elicited burst swimming, occurred within a 0.28 m^2 × 0.36 m round tank for a duration of five minutes (shaded area). All values are percent resting with resting equal to 100%.

Reproductive Activity and Individual Fitness

There is a large suite of possible fitness related effects that may be manifested following catch-and-release angling (Table 1). Several studies have assessed the effects of chronic stress on hatchery fish and have concluded that it can result in smaller egg size, delayed ovulation, and reduced larval survival relative to control fish (Campbell et al. 1992,1994). Booth et al. (1995) found that late season catch-and-release angling had minimal effect on gamete viability of adult Atlantic salmon. In contrast, Pankhurst and Dedual (1993) documented changes in reproductive hormones resulting from catch-and-release angling, but suggested that it is unlikely that these changes would alter reproductive activity. Both studies did, however, propose that angling could disrupt other aspects of reproduction such as nest digging behavior, spawning intensity, or redd defense (Booth et al. 1995) and may have an inhibitory effect at earlier stages of sexual maturity (Pankhurst and Dedual 1993).

Direct assessments of the fitness impacts of catch-and-release angling, however, are difficult and rare, but represent an important component of the issue. To date, the only conclusive link between the stress resulting from catch-and-release angling and failed reproduction of wild fish was found for centrarchids, in which the male provides sole parental care. In this circumstance, the angling of the male has obvious implications for white muscle disturbance (Kieffer et al. 1995). Locomotory impairments following catch-and-release events reduced the ability of the male to defend his brood successfully (Cooke et al. 2000). Furthermore, during the temporary removal

Table 1. Suite of possible fitness impacts resulting from catch-and-release angling.

Possible fitness impacts
• Smaller egg size
• Delayed ovulation
• Reduced gamete viability
• Reduced larval survival
• Reduced larval energy
• Changes in reproductive hormones
• Interruption of migration
• Reduced spawning intensity
• Reduced parental care
• Impaired competitive ability (mates, space)
• Inhibited sexual maturation
• Failed/foregone reproduction

of the male from the nest, predators may consume the developing offspring. Substantial brood predation often results in male abandonment and the subsequent destruction of the entire brood, leading to a reduction in the lifetime reproductive success of the male (Philipp et al. 1997). The centrarchid reproductive life history provides an ideal system for studying fitness impacts of angling, and forthcoming research from our laboratory will attempt to address this issue.

What is the Appropriate Approach?

To assess the pros and cons of catch-and-release angling, a critical first step involves determining the organizational level at which it is most appropriate to assess impacts. Most fisheries managers are concerned with population or community level impacts. Studies that assess the effects of stress at these organizational levels, however, usually do not provide information on how those stress effects are manifested by individuals (Maltby 1999). Molecular and cellular level studies provide insights into metabolic and biochemical disturbances from exercise, but this information has limited applicability at higher organizational levels. Maltby (1999) argues that there is no correct level to study stress. Instead, she advocates studies that integrate information from several levels (also see Adams 1990), which will provide more comprehensive insights into the effects of stress, the mechanistic bases, and their ecological and evolutionary consequences. Similar to ecotoxicologists, researchers examining the effects of catch-and-release angling on individuals face the challenge of ascribing ecological relevance to the putative resultant stresses. At the population level, one might ask, what does it matter if the behavior, physiology, or survival of an individual fish is impaired? There have been a few studies that have evaluated the impacts of catch-and-release angling at a variety of biological levels, including some at the level of the population (Heath 1990).

To understand the effects of catch-and-release angling on all relevant biological levels, a variety of methodologies must be employed. We propose a series of criteria that embody some of the most robust and desirable methodologies for measuring stress and recovery (Table 2). Studies that satisfy the requirements of an ideal monitoring technique will be the most useful in assessing how organisms respond to different stressors; yet, it is clear that few current methodologies can satisfy many of these criteria.

Integrated approaches will provide the most comprehensive and robust information on the effects of catch-and-release angling. Extrapolating these findings to organismal fitness, bioenergetics models, and more widespread effects at the population level will provide the most complete picture as to the true impacts of catch-and-release angling. Such an interdisciplinary approach is very different from the way that these studies typically have been undertaken.

Prospectus for Marine and Freshwater Systems

Field Studies

Intrinsic to freshwater and marine environments are several characteristics that impose both technological and logistic constraints. Freshwater systems generally have fairly low conductivities, permitting the use of radio transmitters. Marine environments have high conductivities that rapidly attenuate short wavelength radio signals, thus requiring the use of ultrasonic transmitters. Attenuation rates can still be a limiting factor for some freshwater applications, such as monitoring fish residing at considerable depth, and consequently, the use of ultrasonic telemetry may be more appropriate than radio transmitters. Conducting telemetry studies in marine environments can be particularly difficult considering the vast area and great depths that fish may occupy. Some groups of fishes are localized and spend much of their lives associated with spatially-restricted habitats such as lagoons, but many species, including a large number of important recreational species (i.e., billfish), live in pelagic environments and can move great distances. Although it is inherently more difficult to obtain telemetric information in marine environments, some approaches and techniques used in freshwater environments may permit the collection of some relevant data on marine catch-and-release angling impacts. For example, it would be possible to capture certain species for telemetric implantation and release into enclosures. After an appropriate recovery period, catch-and-release angling experiments could be performed on those fish, allowing real-time monitoring of the energetic expenditure during the angling, as well as the duration of recovery needed following the event.

Table 2. Desi

Characteristic
Objective and quantifiable
High resolution real time
Not terminal
Free-swimming
Adequate contr basal levels
Recovery/suble effects
Metabolic indic energetics
Fitness

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Table 2. Desirable characteristics for an "ideal" approach to the assessment of catch-and-release impacts.

Characteristic	*Description*
Objective and quantifiable	Central to any monitoring tool is the need to collect data that is objective and quantifiable. These types of data increase the ease of statistical analysis and remove the subjectivity that may bias results
High resolution – real time	Data can be collected on several different time scales. Tools that facilitate the real time monitoring of stress and recovery will be more likely to detect physiological disturbances. Studies that acquire data before, during, and after a perturbation will be the most useful in monitoring the physiological and behavioral status of the organism. Further, a nearly continuous data stream eliminates unknowns during times when fish were not being monitored and permits better trend through time detection.
Not terminal	Sampling methods that, themselves, do not result in the death of the organism, nor alter the behavior and physiology of the organism are important.
Free-swimming fish	Studies that focus on the in situ measurement of free-swimming fish during environmental perturbations will reflect the site-specific characteristics that are faced by the individual. These studies will also be able to detect how fish respond in their natural environment in the presence of the multitude of factors that are difficult to recreate in laboratory conditions (e.g., predation, habitat heterogeneity, etc.).
Adequate controls/ basal levels	Catch-and-release angling studies rarely have true controls or sham controls. Studies that compare fish that have been disturbed to those that have not been recently disturbed allows for greater justification in the attribution of findings to the perturbation being studied, and eliminates the problems associated with nuisance variance. Also, by monitoring individuals prior to disturbance, it will be possible to have complete records of basal levels, disturbance effects, and the subsequent recovery.
Recovery/sublethal effects	Monitoring techniques that provide information on the time required for different disturbances to normalize are required. Studies that are able to monitor recovery and detect sub-lethal effects are essential to understanding and quantifying the behavioral and physiological disturbances associated with catch-and-release angling that do not result in mortality.
Metabolic indicators/ energetics	Stressors and responses that can be quantified in an ecologically common currency (energy) will be useful for inferring the bioenergetic consequences of angling practices and will allow for more relevant comparisons between unrelated taxa.
Fitness	Experimental tests designed to determine the long-term impact of stressors on absolute fitness (lifetime reproductive success) or on fitness-related characters (e.g., fecundity, body condition, age at maturation) will be instrumental in developing a truly complete assessment of impacts of catch-and-release angling.

Marine telemetry studies of recreational fish often target larger-sized individuals than studies conducted in freshwater environments. Their size permits the attachment of devices that are also larger in size. It is often difficult to work with large fish, however, because they typically move through vast areas and do not do well in captivity. Some fishes, such as tunas, congregate in schools that can be followed by boat for days at a time. Devices that relay real-time information could be deployed on these fish, with data collected remotely from vessel-borne receiving systems. This approach has been used for locational data collection on a short-term basis (i.e., hours) for several marine species, such as tarpon *Megalops atlanticus* (Edwards 1998).

For those cases in which animals cannot be tracked directly, the use of archival or satellite-linked systems may be possible. These types of systems are commonly used on marine mammals and birds (e.g., Schreer and Kovacs 1997; Burns and Castellini 1998; Hooker and Baird 2001; Schreer et al. 2001b), but there are several key characteristics of these animals that make the use of these approaches more easily applicable than with fish. Many marine mammals and birds have strong site fidelity that increases the chances of recapturing study animals and consequently recovering archival recorders. Furthermore, the fact that all pinnipeds and marine birds have terrestrial phases further increases the chance of recovering equipment, as well as reducing logistical difficulties. Lastly, being air-breathers, all marine mammals and birds must periodically spend time at the surface to replenish oxygen reserves. This behavior enables antennas necessary for satellite transmissions to be above the water surface for at least a limited period of time, allowing for periodic data transmission to satellites. Fish have few of these characteristics, making the use of archival or satellite-linked systems much less feasible. One solution allowing the application of satellite technology to fish is the use of pop-up systems (e.g., Block et al. 1998). Satellite pop-up transmitters jettison when a corrosive release mechanism gives way. The transmitters rise to the surface of the water and transmit data to satellites. To date, these transmitters have focused on collecting water temperature data, permitting the determination of locations based upon ocean current temperatures. One of the few published studies using this technology (Lutcavage et al. 1999) angled the majority of the fish they monitored, although the results were not discussed in a catch-and-release framework.

Although there are currently no examples of the use of physiological telemetry in marine environments to assess the effects of catch-and-release angling, there are several examples of energetic and ecophysiological studies that provide direction for future angling studies. Sureau and Lagardère (1991) remotely monitored the heart rate and locomotory activity of sole *Solea solea* and sea bass *Dicentrarchus labrax*. Fish were released into a rectangular net pen (length 10 m, width 3 m) in a large seawater pond with direct connection to the ocean. Although these fish were only monitored for a short period of time, this type of controlled experiment coupling physiological and behavioral approaches could be used to study catch-and-release angling disturbance and recovery.

Net pens have been used for physiological telemetry studies, but such approaches have not yet been applied to catch-and-release angling impact assessments. In addition to net pens or large cages, experimental ponds or mariculture facilities operated by academic institutions, government agencies, or private organizations also provide opportunities to conduct physiological telemetry studies on the impacts of catch-and-release angling. In addition, the localized home range of some species could be exploited to collect information on free-ranging fish, if they reside in a spatially restricted area.

Devices that could be applied quickly to marine fish following capture could be used to collect information on free-swimming fish postrelease. Because those fish would have already been captured, it would be difficult to obtain baseline values and control for tagging effects. Since most of the physiological telemetry devices require anesthetization and surgery for attachment or implantation, such approaches are less feasible. Some devices, however, can be attached rapidly without anesthetization. In addition, by following an individual fish by boat, it would be possible to collect physiological data from acoustic physiological transmitters in a manner similar to tracking marine fish tagged with acoustic locational transmitters (e.g., Jolley and Irby 1979).

Laboratory Studies

Although we encourage collecting in situ data from free-swimming fish, it is important to note that controlled laboratory experiments can also provide important information. Reidy et al. (1995) compared the postexercise metabolic rates of Atlantic cod *Gadus morhua*, using several different exhaustion protocols including swimming challenges (i.e., u-crit, u-burst) and chasing tactics. Studies that include angling as an exhaustion method would provide the opportunity to assess which controlled exhaustion protocol most closely resembles that of angling fish in the wild. In some cases, minor changes in laboratory-based exercise protocols to increase their realism (e.g., through air exposure or other simulated handling practices) would increase validity. Large marine teleosts have also been exercised in respirometers (Graham et al. 1990; Dewar and Graham 1994), while, in some cases, also monitoring heart rate and stroke volume (Korsmeyer et al. 1997). These studies have some application to catch-and-release, although no study attempted to examine it directly. It should be noted, however, that wild free-swimming fish and wild fish held in captivity typically respond differently to stress. The difference in response can be highly variable, especially between species (Pickering et al. 1989).

The continued development and refinement of devices capable of remotely measuring biologically relevant parameters would continue to expand our ability to study the response of fish to angling and handling-induced stressors. One promising technique just now in development is the use of videographic recording devices that can be affixed to the organism. This technology already has been applied to marine mammal studies (Marshall 1998). As often is the case, fisheries applications of this technique will have to wait for the further miniaturization of electronic components, in particular, the constraints associated with power supply (battery size). Advances will also be required for free-swimming fish to accommodate devices attached in and around sensitive tissue for extended periods of time.

Conclusions

Fisheries managers should become more aware of the value of behavioral and physiological responses of fish in evaluating the effects of catch-and-release angling. Scientists must also attempt to codify more direct links between their findings and management implications (Loftus 1987). Ultimately, however, it is up to the fisheries scientist to provide managers with scientifically justifiable data that provide direction for the management of recreational fisheries. The imposition of regulations without suitable scientific backing will lead to poor levels of acceptance and compliance (American Fisheries Society 1995). With increasing ethical concerns over various aspects of angling (Balon 2000), quantifiable and objective measures of animal welfare are becoming more valuable. We also need to stop setting mortality as the end measure of the effects of catch-and-release angling. Information on sublethal effects will help managers to design and impose regulations designed to minimize the negative impacts of catch-and-release angling on fish, especially those that affect long-term fitness. Collecting this type of information will not be easy, but it will provide better evidence on the biological effects of catch-and-release angling. It may also be expensive; most of the approaches outlined in this paper require significant expenditure of capital. The question is whether we adopt a proactive approach by gathering appropriate data and enacting rational management decisions now, or take a reactive approach by waiting to deal with problems only as they arise. Those problems could range from collapses of fisheries to pressure from animal welfare constituencies to stop catch-and-release angling.

Many of the approaches outlined in this paper are applicable to the assessment of catch-and-release angling in both marine and freshwater systems. The challenge is to implement these approaches now. As fisheries managers, we need to realize that, although the population is the fundamental management unit of concern, we must begin by gaining an understanding of the effects that catch-and-release angling has on the individual. We need to focus on providing complete answers to difficult questions. There is no doubt that from the perspective of the individual fish, there is more to just surviving a catch-and-release angling event; we must consider these issues in a broader energetics and fitness framework.

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