Thiamine Deficiency in Aquatic Food Chains
The Cumulative Result of Ecosystem Disruption by Clupeids?

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Clupeid fish such as herring (Clupea spp), shad (Dorosoma spp), and alewives (Alosa pseudoharengus) have long been recognised as a source of thiaminase activity in aquatic food chains throughout North America and the Baltic Sea (Deutsch and Hasler, 1943; Neilands 1947; Gnaedinger and Krzeczkowski, 1966; Ji and Adelman, 1998; Tillitt et al., 2005; Honeyfield et al., 2007; Wistbacka and Bylund, 2008). Thiaminase is an enzyme, possibly of bacterial origin (Honeyfield et al., 2002; Tillitt et al., 2005), which is thought to be involved in the destruction of thiamine in the gut of predators that consume prey fish containing thiaminase. This leads to reduced uptake of thiamine by clupeid predators and eventually thiamine deficiency if thiaminase activity is high enough and clupeids comprise a high enough proportion of the diet (Honeyfield et al., 2005). When fish containing high levels of thiaminase are fed to captive foxes or mink, this results in Chastek paralysis (Green et al., 1937; Deutsch and Hasler, 1943). Similarly on fish farms, salmonines fed fish containing high levels of thiaminase also develop thiamine deficiency (Allan, 1958; Saunders and Henderson, 1969). It should be noted, however, that in spite of their high thiaminase content, species like alewives appear to contain adequate thiamine levels to support fish nutrition (Saunders and Henderson, 1974; Honeyfield et al., 2005; Fitzsimons et al., 1998, 2005b; Tillitt et al., 2005).

Clupeids contain some of the highest thiaminase levels reported in aquatic organisms (Tillitt et al., 2005; Honeyfield et al., 2005, 2007; Wistbacka and Bylund, 2008). It is only recently, however, that the process by which clupeids exert aquatic ecosystem disruption and cause thiamine deficiency with this enzyme has become evident. In the laboratory, it is possible to cause thiamine deficiency in captive fish fed a diet consisting exclusively of clupeids (Saunders and Henderson, 1974; Honeyfield et al., 2005). In the wild, this was thought to be unlikely, however. Diets in the wild consisting predominantly of prey from a diverse prey community, either lacking or having low levels of thiaminase, were believed to reduce the overall influence of individual prey fish species containing high levels of thiaminase. As a result, having thiaminase-rich prey in the diet was thought to be tolerable for a limited period of time (see Saunders and Henderson, 1974). Predators of clupeids including Atlantic cod (Gadus morhua) from the Gulf of St Lawrence have apparently tolerated a diet comprised of Atlantic her-
ring (*Clupea harengus*) when that diet also included euphausiids, shrimp, crab, mysids, capelin and polychaetes (Hanson and Chouinard, 2002). Similarly, Baltic salmon (*Salmo salar*) apparently tolerated a diet of sprat (*Sprattus sprattus*) and Baltic herring (*Clupea harengus membrus*) that also included other prey such as three-spine stickleback (*Gasterosteus aculeatus*), perch (*Perca fluviatilis* L.), smelt (*Osmerus eperlanus* L.), sandeel (*Ammodytes sp.*), bream (*Abramis brama* L.) and eelpout (*Zoarces viviparus* L.) for millennia in the Baltic Sea (Hansson et al., 2001; Wistbacka and Bylund, 2008).

In contrast to the conditions described above where predators appeared to co-exist with clupeids containing high levels of thiaminase in their diet, such is not the case for salmonines in the North American Great Lakes, as is best typified by lake trout (*Salvelinus namaycush*) (Fitzsimons et al., 2003). As a result of aggressive stocking programs, the abundance of adult lake trout in the Great Lakes has increased markedly from its former depressed state that was the result of overexploitation and sea lamprey (*Petromyzon marinus*) parasitism (Hatch et al., 1981; Holey et al., 1995; Rutherford, 1997; Hansen, 1999; Bronte et al., 2007). Despite these efforts, many of these lake trout stocks, especially in Lakes Ontario and Michigan but less so in Lake Huron, show little evidence of significant natural reproduction (Madenjian and DeSorcie, 1999; Madenjian et al., 2004; Fitzsimons et al., 2003). All of these stocks are dependent on alewives (Lantry, 2001; Madenjian et al., 1998, 2006). Predation by alewives on larval lake trout has been proposed as a major contributor to the lack of natural reproduction by lake trout in the Great Lakes, based on work conducted in Lake Ontario but the results are ambiguous, being confounded by simultaneous changes in lake trout egg deposition indices and the potential for thiamine deficiency to affect vulnerability of larval lake trout to alewife predation (Krueger et al., 1995, O’Gorman et al. 1998, Fitzsimons et al. 2009a, unpublished data). A shift in the spingtime distribution of alewives to further offshore in Lake Ontario (O’Gorman et al., 2000) and away from the majority of lake trout spawning reefs in this lake was associated with a significant increase in lake trout natural reproduction (Fitzsimons, 1995; Perkins and Krueger, 1995; unpublished data). Although proof that alewife predation was exerting a negative effect, the absence of a major and sustained increase in the amount of natural reproduction by lake trout suggests that other factors in addition to alewife predation may be limiting lake trout reproduction in Lake Ontario (Fitzsimons et al., 2003; B. Lantry pers. comm.). Thiamine deficiency effects are implicated since lake trout egg thiamine concentrations remained unchanged between 1994 and 2004 (Fitzsimons et al., 2007), but the effects of the deficiency in Lake Ontario will remain of uncertain importance until there is a major change in lake trout diets and its effect on natural reproduction can be assessed. For Lake Huron, Fitzsimons et al. (2009b) reported that relief from the thiamine-reducing effects of alewives made a greater contribution than relief from alewife predation to increased natural reproduction by lake trout following the collapse of alewives in this lake. As a result of their high thiaminase content, the potential for alewives to have unique depensatory effects on predators like lake trout in the North American Great Lakes may be widespread (Walters and Kitchell, 2001). An understanding of the mechanisms leading up to this depensation has remained incomplete until only recently as the implications of the dominance of a thiaminase-rich prey fish such as alewives in the diets of top predators have become more fully understood.

There are several recent, although indirect, examples from both marine and freshwater environments that when clupeids become abundant enough in the diet of a predator, they can negatively affect recruitment and this may be related to their high thiaminase content. For example the most productive period of Atlantic salmon in the north-east Atlantic Ocean was associated with the collapse of Norwegian spring-spawning herring (*C. harengus*), a species that was formerly their major food source and is known to be thiaminase-rich (Wistbacka et al., 2002; Haugland et al., 2006). Similarly, a recent increase in recruitment of lake trout occurred in Lake Huron following the collapse of alewife in this lake (Riley et al., 2007). Prior to their collapse, alewives had been one of the most important diet items of lake trout in Lake Huron (Madenjian et al., 2006). The situation in Lake Champlain mirrors that in Lake Huron in that the recent addition to and subsequent expansion of alewives in Lake Champlain reduced egg thiamine in lake trout (unpublished data) and resulted in high levels of Cayuga Syndrome (Fisher et al. 1996), a thiamine deficiency mortality syndrome, in the
progeny of resident Atlantic salmon (K. Kesley, VDNR, Grand Isle, VT, pers. comm.). Prior to alewives occurring in Lake Champlain, there had been no evidence of Cayuga Syndrome in resident Atlantic salmon. Collectively, this suggests that high consumption of prey fish containing high levels of thiaminase, e.g. clupeids, can under certain circumstances impose negative impacts on fish stocks. The conditions under which this occurs and the full range of biological effects have only recently been elaborated and are the subject of this review.

**Effects of Thiamine Deficiency by Life Stage and Relationship to Recruitment**

As a disruptor of ecosystem function, the effect of thiamine deficiency resulting from a high thiaminase diet has few parallels in nature in terms of the magnitude of potential negative effects. Thiamine deficiency appears fully capable of causing mortality and other effects at multiple life stages and as a result has the potential to block reproduction in a variety of top predators, leading to population declines and possibly even extinctions (see Ketola et al., 2000).

For Great Lakes Basin salmonines, the acute mortality effects of thiamine deficiency affecting embryonic stages have been the most obvious and hence the most studied effects (Fitzsimons, 1995; Fisher et al., 1996; Marcquenski and Brown, 1997; Brown et al., 1998). These effects are referred to as Early Mortality Syndrome or EMS in Great Lakes salmonines or Cayuga Syndrome in Finger Lakes Atlantic salmon. The involvement of thiamine in their aetiology has been confirmed in that the syndromes can be both reduced by thiamine prophylaxis (Fitzsimons, 1995; Fitzsimons et al., 2001a; Brown et al., 2005a) and induced by thiamine antagonists (Amcoff et al., 1999; Fitzsimons et al., 2001a, b). Their presence has been linked to reduced egg thiamine levels, which have been directly related to the amount of alewives in maternal diets (Fitzsimons et al., 1999; Fitzsimons and Brown, 1998; Brown et al., 2005b, c; Fitzsimons et al., 2007; Fisher et al., 1996; Honeyfield et al., 2005).

Mortality alone seems insufficient to explain the recruitment failure of lake trout associated with consumption of alewives. Acute mortality resulting from EMS, which ranges from approximately to 20 to 30% (Fitzsimons et al., 1999), but can be upwards of 70% (Fitzsimons et al., 2007), is generally insufficient to totally block reproduction by lake trout. Nevertheless ongoing recruitment failure in stocks exhibiting thiamine deficiency (Fitzsimons and Brown, 1998), coupled with a lack of other plausible explanations (Fitzsimons et al., 2003), suggests thiamine deficiency may be imposing effects in addition to acute mortality that can lead to recruitment failure. This notion prompted investigation into the effects of thiamine deficiency on the larval growth, foraging and predator avoidance of lake trout, because these early life history attributes have well-established links with early survival. This culminated in research reported by Fitzsimons et al. (2009a), who found a direct relationship between larval lake trout growth, foraging rate, and predator avoidance, and egg thiamine concentration. Of these effects, growth impairment was apparently the most sensitive effect of thiamine deficiency. The threshold egg thiamine concentration established by these authors for a 50% decline in growth (5.1 nmol/g) was approximately three-fold higher than what they had previously reported for 50% EMS (1.6 nmol/g) (Fitzsimons et al., 2007). By relating their growth effect threshold to the current distribution of egg thiamine levels in lake trout, these authors estimated that for Lakes Erie, Ontario and Michigan, 46, 77, and 97% of lake trout families, respectively, would spawn eggs with at least a 50% reduction in growth. This was compared with 0, 46 and 38% of lake trout families from Lakes Erie, Michigan and Ontario, respectively, having egg thiamine concentrations resulting in 50% or greater EMS. While it might be argued that reduced growth in and of itself is not directly lethal, reduced growth may contribute to mortality and ultimately recruitment failure. Growth directly affects size and size is directly related to swimming speed (Blaxter, 1986; Webb and Weihs, 1986). Reduced swimming speed makes larval fish more susceptible to predation (Blaxter, 1986; Werner and Gilliam, 1984; Zaret, 1980; Brooking et al., 1998) while reducing foraging efficiency (Blaxter, 1986; Webb and Weihs, 1986), both of which can contribute to mortality in the wild (Miller et al., 1988; Houde, 1997). In support of the notion that sublethal effects may be a significant but unrecognised impact of thiamine deficiency, Fitzsimons et al. (2009b) found that a fry emer-
gence index (FEI) for larval lake trout in Lake Huron was directly related to egg thiamine concentration. The occurrence of EMS in their study was relatively low (e.g. <15%). They attributed the thiamine effect on FEI to a greater susceptibility of thiamine-deficient fry to predation by crayfish, which may have been exacerbated by the altered behaviour of thiamine-deficient fry making them both more readily detectable (e.g. hyperexcitability) and attacked (e.g. lethargy, loss of equilibrium).

Thiamine levels of adult salmonines feeding heavily on alewives appear to be negatively affected by such a diet based on comparisons of tissue thiamine concentrations between populations having a high proportion of alewives in their diet and populations having a much smaller proportion of alewives or no alewives at all (Brown et al., 2005d). Negative effects resulting from such depressed levels have been reported for adults of several species of salmonines. Effects include altered behaviour (Brown et al., 2005d), impaired migration (Ketola et al., 2005), impaired spawning habitat use (Ketola et al., 2009) and mortality (Fitzsimons et al., 2005a).

Mortality in the wild of adults affected with thiamine deficiency may be quite high. Fitzsimons et al. (2005a) discussed at least two instances of massive die-offs of Lake Michigan coho salmon (Oncorhynchus kisutch) during 2001 in Platte Bay prior to fish entering the Platte River on their spawning run in 2001. In contrast, females entering the lower part of the river in the same year as the die-offs occurred exhibited few signs of thiamine deficiency (e.g. lethargy) and had muscle thiamine levels averaging 0.97 nmol/g, which was above the 0.59 nmol/g level associated with lethargy (Brown et al., 2005d). The upstream spawning migration of coho salmon on the Platte River affected thiamine levels since the signs of thiamine deficiency (e.g. lethargy) increased to approximately 20% in fish reaching a hatchery 15 km upstream of where fish first entered the Platte River (Fitzsimons et al., 2005a). Thiamine levels in fish exhibiting thiamine deficiency signs at the hatchery were less than half those of fish first entering the river. Associated with increased signs of thiamine deficiency was co-occurring mortality, which was significantly reduced in coho salmon given a thiamine injection upon entry into the river. Similarly for Lake Ontario Chinook salmon (O. tshawytscha) ascending the Salmon River in 2004-2005, there was upwards of 60% pre-spawning mortality (Everitt, 2006). Gradient and flow on the Salmon River during the time that Everitt (2006) conducted his studies was much higher than on the Platte River when Fitzsimons et al. (2005a) conducted their studies (Ketola et al., 2009). Although part of the Chinook salmon mortality occurring on the Salmon River may have been related to the effects of angling (Bendock and Alexandersdottir, 1993) or temperature stress (Richter and Kolmes, 2005), mortality was still higher than expected. Subsequent work with Lake Ontario Chinook salmon (Fitzsimons et al. 2011a; Figure 20.1) has revealed extremely low muscle thiamine concentrations in Lake Ontario Chinook salmon which are at or below levels associated with lethargy in other salmonines (Brown et al., 2005d; unpublished data). Thiamine deficiency, because it causes increased plasma concentrations of lactate (Combs, 1992), would have exacerbated the negative effects of angling and temperature stress that lead to the build-up of lactic acid in the blood and that have been associated with mortality (Wood et al., 1983). In addition, thiamine plays a central role in the production of ATP equivalents that support metabolism. As a result, during periods of vigorous activity such as that caused by angling or high temperature there may be additional demands on thiamine reserves and if these are already depleted by a thiaminase containing diet mortality may result (Fitzsimons et al., 2005a).

Relatively little is known about the effects of thiamine deficiency at the juvenile stage, even though they may be feeding on much the same prey as adults, including alewives (Madenjian et al., 1998). Juveniles appear to be more sensitive to the effects of thiamine deficiency than adults (Morito et al., 1986; Ketola et al. 2008). Recent work in Lake Ontario on the ontogeny of thiamine deficiency in lake trout suggests there is a strong potential for effects to occur throughout almost the entire period of piscivory including the juvenile period. Alewives are the most significant prey species in the diet of salmonines in Lake Ontario (Lantry, 2001) and both lake trout (Fitzsimons et al. 2011b; Figure 20.1) and Chinook salmon (Figure 20.2) show evidence of ontogenetic declines in muscle thiamine relative to reference populations. Such declines are presumed to represent a diet containing a high proportion of alewives. This is based on the knowledge that as well as being dominant in the diet of salmonines, alewives are the major prey species in Lake Ontario (Owens et al., 2003).
Analysis of stomach contents and stable isotopes confirms the fact that alewives are the dominant diet item for both lake trout and Chinook salmon (Fitzsimons et al. 2011a, b). Reference populations used to establish the degree of thiamine deficiency in Lake Ontario lake trout had either lesser amounts of thiaminase-containing prey (e.g. rainbow smelt (*Osmerus mordax*) and alewives; Harvey and Kitchell, 2000) (e.g. Lake Superior) or no thiaminase-containing prey in their diet (e.g. Spray Lake). A small proportion of juvenile lake trout in Lake Ontario had muscle thiamine levels similar to those associated with acute mortality in captive adult lake trout (Brown et al., 2005d), whereas a larger proportion had levels at or below those associated with altered behaviour (Brown et al. 2005d) that could increase susceptibility to predation (Mesa, 1994; Carlson et al., 1998; Conte, 2004; Ketola et al., 2009). As a result, the effects of thiamine deficiency on juveniles may be extensive. It is noteworthy that following a decline in slimy sculpins in Lake Ontario (Owens et al., 2003), there was a coincident drop in the survival index for three-year-old lake trout their major predator (B. Lantry, USGS, pers. comm.; Owens and Bergstedt, 1994). Sculpins essentially lack thiaminase (Tillitt et al., 2005), and historically comprised the bulk of the diet of juvenile lake trout in Lake Ontario (Elrod and O’Gorman, 1991). At the time of the sculpin decline, alewives were the next
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most abundant prey fish in Lake Ontario and thus most likely replaced sculpins in lake trout diets. Other potential prey fish were either less abundant or declining (e.g. smelt), or of such low abundance (e.g. emerald shiner (*Notropis atherinoides*), three-spine stickleback) that they were unlikely to make a contribution to lake trout diets (Owens et al., 2003). Therefore it seems reasonable to conclude that when slimy sculpins declined, juvenile lake trout switched their diet from one that was thiaminase-poor (e.g. sculpin) to one that was thiaminase-rich (e.g. alewife). As a result, lake trout may have suffered direct and indirect mortality from thiamine deficiency effects, but more work is required to confirm this.

### Ascendancy of Clupeids in Aquatic Food Chains and Trophic Cascade Effects

Having demonstrated that significant negative impacts can result from thiamine deficiency in Great Lakes salmonines, potentially blocking natural reproduction for lake trout (Fitzsimons et al., 2003; Bronte et al., 2003) and Atlantic salmon (Ketola et al., 2000), emphasis has switched to understanding causes and how to manage the problem. This includes the particular reasons why clupeids such as alewives should reach such high levels of abundance to nearly dominate prey communities and as a result dominate predator diets. It is also of interest to know why clupeids of all fish should have such high thiaminase levels and what factors regulate thiaminase activity, and finally what, if anything can be done to mitigate effects.

Large dominant top predators that are at the top of food chains are successful in part because of ‘cultivation’ effects where they crop down forage species that are potential competitors or predators (Walters and Kitchell, 2001). Due to their relatively high fecundity and tolerance of a wide range of environmental conditions (Scott and Crossman, 1973), and innate capacity to recover after catastrophic declines, clupeids have the potential to readily exploit a reduction in predation pressure from such top predators, allowing them to achieve rapid population expansion and reach high levels of abundance (Smith 1970; O’Gorman and Schneider 1986; Hutchings and Reynolds, 2004). This high abundance when coupled with diverse feeding habits (filter feeding, particle feeding; Janssen, 1976) and competition with and predation on other prey fish, allows clupeids such as alewives to suppress other prey fish (Madenjian et al., 2008; Bunnell et al., 2006). Such was the case for alewives in the Great Lakes where they have been strongly implicated in the suppression of several native species although documentation of effects on cisco (*Coregonus artedii*) until recently were largely circumstantial and thought to be without merit (Crowder, 1980, 1986; Madenjian et al., 2008; Bunnell et al., 2006). Cisco was historically one of the most important prey fish in all five of the North American Great Lakes (Fitzsimons and O’Gorman 2006). As early as the 1800s it was speculated that the expansion of alewives in Lake Ontario following the loss of Atlantic salmon the top predator (Smith 1892), had resulted in dramatic declines in cisco (Mather, 1881), considered to be one of the most abundant species prior to the invasion of the lake by alewives in 1873 (Rathbun and Wakeham, 1897). However, Madenjian et al. (2008) presented evidence that cisco are only minimally affected by alewife because the time window for alewife to predate on larval cisco is small as a result of limited overlap in habitat. Nevertheless, Dunlop et al. (2010) provided evidence for Lake Huron of increased abundance of cisco following the collapse of alewives in this lake. Their observations when combined with those of others finding increased cisco abundance following the decline of alewives (Dobiesz et al., 2005; Warner et al., 2009) strongly implicate alewives in suppressing cisco populations. Although the shift from alewife to cisco in Lake Huron suggests relief from either predation or competition, the nature of the negative interaction between alewives and ciscoes has not been established. It may involve changes in the abundance of large zooplankters such as *Limnocalanus*, since alewife planktivory is highly size-selective and has been implicated in regulation of *Limnocalanus* in Lake Michigan (O’Gorman et al., 1991, Barbiero et al., 2009). Alternatively a negative interaction may be the result of reduced predation by alewives on young of the year but not egg and larval stages of cisco, since the seasonal depth distribution of alewives does not overlap the spawning habitat of cisco (Wells, 1968).

As a result of their potential to attain high population abundance while suppressing alternate prey species, clupeids can in turn dominate the diets of predators. This
would be more likely to occur when the population control formerly provided by a predator was interrupted for a sufficient period of time to allow clupeid populations to build up to a high level and become dominant. For example, evidence of large alewife populations, usually evident as major die-offs (Brown, 1972; O’Gorman and Schneider, 1986), were not documented until the 1960s and 1970s even though alewives first entered the Great Lakes in the 1800s (Ketola et al., 2000) and by the 1950s were found in all of the Great Lakes. In Lake Michigan, proliferation of alewives did not occur until approximately one decade after the crash of the lake trout population in this lake, which was due to a combination of overfishing and sea lamprey parasitism (Hatch et al., 1981; Holey et al., 1995; Rutherford, 1997). This pattern was repeated throughout the Great Lakes (Smith, 1995). High clupeid population abundance can be sustained even if predator abundance returns to near normal, as is evident for the Great Lakes (Madenjian et al., 2002; Mills et al., 2003). Despite the restoration of lake trout stocks in Lake Michigan by stocking, first begun in the mid-1960s and which continues today (Holey et al., 1995), large populations of alewives persist in the face of large adult stocks of lake trout that have resulted from over four decades of stocking, and which consume primarily alewives (Madenjian et al., 1998, 2002; Bronte et al., 2007).

The pattern of ecosystem change associated with a build-up in clupeid abundance and development of thiamine deficiency that follows declines in the abundance of the top predator, appears to be similar across ecosystems and has been attributed to multi-level trophic cascades (Harman et al., 2002; Casini et al., 2008, 2009). Recent changes in the Baltic Sea show a similar chronology to the Great Lakes, of a build-up in clupeid abundance, in this case sprat and Baltic herring, following the loss of the top predator, in this case Baltic cod. The loss of cod has been related to a period where saltwater intrusions from the North Sea did not occur. The ensuing stagnation of the Baltic Sea resulted in a significant decline in Baltic cod as a result of embryonic mortality caused by low dissolved oxygen (Mackenzie et al., 1996). The decline in cod was followed by a dramatic increase in the abundance of sprat and Baltic herring (Sparholt, 1994). Despite partial recovery of dissolved oxygen levels following a major inflow to the Baltic Sea from the North Sea in 1993 (Matthaus and Lass, 1995), cod recruitment remained low, suggesting that other processes were limiting reproductive success (Bagge, 1994). Documentation of extensive cod egg predation by sprat and herring (Koster and Mollmann, 1997) and the resulting development of cod recruitment models (Koster et al., 2001 a, b) revealed that egg predation had become a strong, albeit not the only regulator, of cod recruitment in the Baltic Sea.

The relative influence of clupeid egg predation on cod as a depensatory factor of cod in the Baltic Sea seemed much stronger than possible thiamine deficiency effects. High consumption of clupeids by cod appeared to be without consequence of thiamine deficiency induced embryonic effects usually associated with high clupeid consumption. Instead cod egg thiamine status was not affected (Amcoff et al., 1999), nor was larval survival responsive to thiamine prophylaxis suggestive that cod were able to maintain adequate thiamine nutrition (Mellargaard, 1996; Nissling and Vallin, 1996). Thiamine deficiency effects were in fact more evident in other apparently more sensitive species such as Baltic salmon and sea trout (S. trutta) that presumably have a greater proportion of clupeids in their diet now than before cod declined, as evidenced by reduced egg thiamine concentrations (Amcoff et al., 1999). The build-up in clupeid biomass, elevated occurrence in the diet of salmonines and resulting thiamine deficiency is very similar to the situation for salmonine top predators in the Great Lakes.

Factors Affecting Thiaminase Activity in Clupeids and Their Influence on Thiamine Deficiency

The particular reasons why clupeids consistently have some of the highest thiaminase activity observed amongst teleosts remains unclear (Nielands, 1947; Greig and Gnaedinger, 1971; Tillitt et al., 2005; Honeyfield et al., 2007; Wistbacka and Bylund, 1998). In a review of phylogenetic and ecological characteristics associated with thiaminase activity in North American Great Lakes fishes, Riley and Evans (2008) found, based on diverse measures of thiaminase activity, that taxonomically more ancestral species (Anguilliformes, Clupeiformes, Cypriniformes,
Ictalurus punctatus (Abe et al., 174) activity may be as a result of the effect of lipids on the within alewives, where most work has been done to understand thiaminase dynamics, there is evidence that thiaminase activity varies among seasons, within and among lakes, and is related to the size of alewife (Tillitt et al., 2005; Fitzsimons et al., 2005b) suggesting that a variety of factors may be involved in modulation of thiaminase activity. Whether such factors are related to variation in diet, habitat, or some other factor or factors, is unclear. Fitzsimons et al. (2005b) found that thiaminase activity of Finger Lakes alewives was inversely correlated to lipid level and that lipid level was correlated with lake chlorophyll-\(a\), a measure of lake productivity. As such, lake productivity through its influence on lipid content may influence thiaminase activity. Effects of lake productivity on alewife lipid content is consistent with the timing of a decline in energy density for Lake Ontario alewives between 1978 and 1990 (Rand et al., 1994). For alewives, energy density is directly related to lipid content (Rottiers and Tucker, 1982). Rand et al. (1994) attributed the decline in energy density of alewives, especially during the latter part of the period 1978 to 1990, to a decline in lake productivity, most likely due in part to a decline in zooplankton density (O’Gorman et al., 1997).

Fish lipid content is known to be affected by the lipid content of the diet and feeding rate (Madenjian et al., 2000). Hence the higher thiaminase activity noted by Tillitt et al. (2005) in Lake Michigan alewives in spring relative to summer and autumn may be a reflection of either the lower lipid levels observed in alewives during the spring relative to the summer and autumn (Flath and Diana, 1985), or the lower feeding activity noted for alewives in the spring relative to the summer and autumn (Stewart and Binkowski, 1986), or some combination of these. Thiaminase activity of alewives collected in the winter, the period of lowest feeding activity (Stewart and Binkowski, 1986), was twice that of alewives collected during the summer, when feeding activity is expected to be much higher (unpublished data).

The apparent relationship between lipid and thiaminase activity may be as a result of the effect of lipids on the immune system and health of an organism and possible regulation of thiaminolytic bacteria which have been isolated from alewives (Honeyfield et al., 2002). Fluctuations in alewife thiaminase activity resulting from fluctuations in feeding activity could in turn lead to fluctuations in the expression of thiamine deficiency in alewife predators. Undernutrition due to insufficient intake of energy and/or macronutrients due to deficiencies in specific micronutrients can impair the immune system, suppressing immune functions that are fundamental to host protection (Marcos et al., 2003). Sheldon and Blazer (1991) reported that bactericidal activity in channel catfish (Ictalurus punctatus) was positively correlated with dietary highly unsaturated fatty acids (HUFA). Eicosanoids, which control inflammation and immunity, consist of prostaglandins, prosta-cyclins, thromboxanes and leukotrienes and are primarily derived from the fatty acids arachidonic and linoleic acids (M. Arts, Environment Canada, pers. comm.). A relationship between health and thiaminase activity has been confirmed for common carp (Cyprinus carpio), which exhibited elevated muscle thiaminase activity after injection with live Aeromonas salmonicida (Wistbacka et al., 2009).

Tillitt et al. (2005) felt that there was strong evidence for a bacterial origin for the thiaminase found in fishes. They based this on the thiaminase gene having been cloned in Paenabacillus thiaminolyticus (Abe et al., 1987), these bacteria having been isolated and cultured from the alewife digestive tract (Honeyfield et al., 2002), and the fact that the distribution of thiaminase in fishes is consistent with areas where bacteria are concentrated in fishes (Fujita, 1954; Zajicek et al., 2005). Further, these authors stated that the biochemical characteristics of thiaminase, including temperature and pH optima in fishes, particularly Lake Michigan alewives, were consistent with a bacterial source (see Zajicek et al., 2005). Given the possible role of lipids in immune function, high lipid levels may be involved in down-regulation of thiaminase-producing bacteria, whereas low lipids may be involved in the up-regulation of thiaminase-producing bacteria. This in turn may influence the occurrence of thiamine deficiency in predators, since fluctuations in the thiaminase activity of a particular prey species may lead to fluctuations in the amount of thiamine assimilated from prey species by a predator. Honeyfield et al. (2005) found that thiamine levels in the eggs of lake trout fed mixtures of...
alewives, which are thiaminase-rich, and bloaters, which are thiaminase-poor, were directly related to the average amount of thiaminase activity in the diet.

There appears to be support for the notion that lipid can influence thiaminase activity in clupeids in the wild and affect their potential to cause thiamine deficiency effects. The importance of diet and specifically its influence on lipid stores and resulting thiaminase activity was suggested in work by Wistbacka and Bylund (2008). These authors found, albeit indirectly, that the thiaminase activity of Baltic herring appeared to be inversely related to their lipid content. During the period 1979-1991 when the M74 prevalence in Baltic salmon was low, the fat content of Baltic herring in the main basin of the Baltic Sea was almost twice as high as in the most serious M74 period 1991-2002 (Wistbacka and Bylund, 2008). Wistbacka et al. (2002) had earlier indicated that Baltic herring, with their high thiaminase activity, were the immediate causal factor for the M74 syndrome in Baltic salmon, and this was the case for both time periods.

Variation in prey fish lipid stores and its effect on thiaminase activity may also be responsible for variation in EMS in coho salmon. In Lake Michigan, there was a dramatic upward shift in the occurrence of EMS in coho salmon after 1990, after dreissenids had invaded the lake (Brown et al., 2005b). Coho salmon in Lake Michigan eat alewives almost exclusively, feeding almost exclusively on large alewives in the second year of life prior to spawning (Madajenjian et al., 1998a, b). The lipid content of large (≥ 120 mm) alewives dropped by upwards of 50% following the invasion of Lake Michigan by dreissenids in the late 1980s (Hondorp et al., 2005; Madajenjian et al., 2006b). Madajenjian et al. (2006) attributed the drop in lipid content to the decreased importance of Diporeia in the diet, most likely the result of a decline in Diporeia in Lake Michigan (Nalepa et al., 2005, 2006). Diporeia is relatively high in lipid content (Hondorp et al., 2005) compared with other invertebrates and a decrease in its importance in the diet of alewives would be expected to lead to decreases in both lipid content and energy density of alewives, since the two are correlated (Rottiers and Tucker, 1982; Madajenjian et al., 2000).

Diet may also be a direct source of thiaminase for fish. Increased thiaminase activity was measured in fish exposed to toxic blue-green algae containing thiaminase although the mode of uptake was not described (Arsan, 1970; Arsan and Malyarevskaya, 1969). Zajicek et al. (2005) measured thiaminase activity albeit at low levels in net plankton, Mysis and Diporeia from lakes Michigan and Superior. All of these biota are potential prey of alewives (Hondorp et al., 2005) More comprehensive sampling in Lake Michigan (unpublished data) found thiaminase activity in net plankton and Mysis of up to 20% of the average measured in alewives from this lake (Tillitt et al., 2005). Furthermore, while thiaminase levels were similar in net plankton and Mysis, they were three-fold higher than in Diporeia (unpublished data), suggesting that if diet was an important vector for thiaminase activity in alewives, the composition of the diet could be quite important.

Attempts at experimentally determining the role of different factors in controlling thiaminase activity have had little success but have provided some surprising results in terms of the dynamic nature of thiaminase activity in clupeids. Experimentally stressing Seneca Lake alewives in the laboratory by either varying the salt content of holding water or food limitation in order to induce stress and affect circulating white blood cells (Pickering, 1984; Barton et al., 1987) did not affect their thiaminase activity (Lepak et al., 2008). However, Lepak et al. (2008) found that the thiaminase activity of alewives held in the laboratory and fed a thiaminase free diet prior to experimentation was over two-fold higher than the thiaminase activity of alewives immediately after collection from Seneca Lake. The authors were unable to provide an explanation for this difference. They felt it was unrelated to stress as alewives grew well in the laboratory with little mortality, which they would not have expected had the fish been under stress. Similar effects were seen with Baltic herring held in captivity for 25 days, where there was an elevation in thiaminase activity compared with that of herring immediately after capture (Wistbacka and Bylund, 2008). Whether such changes involve effects on immune function, possibly by modulation of eicosanoid biosynthesis mediated by stress or trauma, remains to be determined. Lack of identification of a factor or factors associated with captivity that causes elevation in thiaminase activity is a major impediment to experimentation and to further understanding of the importance of the regulation of thiaminase activity in alewives.

The North American Great Lakes/St. Lawrence River and Estuary
Relationship between Alewife Abundance and Thiamine Deficiency

Given the ability of alewives to cause thiamine deficiency in proportion to their importance in the diet of laboratory fish a similar relationship would be expected among wild populations although such a relationship if it exists may have changed over time (Honeyfield et al. 2005). Fitzsimons et al. (1999) correlated a measure of alewife abundance with EMS, an indicator of thiamine deficiency; for Lake Michigan these authors reported a significant but negative and weak correlation \( r^2 = 0.14 \) between trawl catch abundance of adult alewife and the occurrence of EMS in coho salmon that ranged from 0 to close to 100%. Of the salmonines found in the Great Lakes coho salmon show the highest consumption of alewives so are likely to be the most responsive to changes in alewife abundance (Jude et al. 1987; Madenjian et al. 1998b; Lantry 2001). These authors used EMS as their measure of thiamine deficiency because of its strong relationship with egg thiamine (Hornung et al., 1998; Honeyfield et al., 1998) and the lack of historical data on thiamine levels at the time. Fitzsimons et al. (1999) were unable to find similar negative correlations between alewife abundance and the occurrence of EMS in Lake Michigan lake trout, which they attributed to the greater diet diversity of lake trout compared to coho salmon (Jude et al. 1987; Madenjian et al., 1998). The results of Fitzsimons et al. (1999) however, seem to run counter to the association established between alewives in the diet and reductions in egg thiamine (Fitzsimons and Brown, 1998; Honeyfield et al., 2005). Moreover the diet of salmonines seems to be opportunistic (Warner et al. 2008) such that salmonines should make the greatest usage of the most abundant food source. Hence during years of high alewife abundance, salmonines should make the greatest usage of alewives and this in turn should result in high EMS, not low EMS, unless other factors are at play. Its noteworthy however, that the data of Fitzsimons et al (1999) was based on all sizes of alewives and it has been established that in the their second year of life, coho salmon fed almost exclusively on large (>120 mm) alewives although smaller amounts of small alewives are also consumed (Madenjian et al. 1998). Moreover the lipid content of large alewives (Madenjian et al 2006b) declined midway through the the time series used by Fitzsimons et al. (1999) and this may have affected alewife thiaminase activity and altered their ability to cause thiamine deficiency (see Fitzsimons et al. 2005b).

Due to the ongoing uncertainty as to the relationship between alewives and the occurrence of EMS in feral fish we reevaluated the relationship between alewife abundance and the occurrence of EMS in families of coho salmon for Lake Michigan using new information. For this we focused on the biomass of large alewives, ages one to three, as they accounted for almost 90% of the biomass of large alewives in Lake Michigan between the ages of one and six during the period 1999 to 2007 (Warner et al. 2008). Alewife biomass for a given year and age was determined from abundance at age three when alewives are fully recruited to bottom-trawl gear using the methods described in Madenjian et al. (2005). We used trawl data collected by the Great Lakes Science Center (see Madenjian et al., 2005). Data on the proportion of coho salmon families with EMS were derived from the records of the Michigan Department of Natural Resources, Fish Health Laboratory (see Honeyfield et al., 1998), which has maintained long-term observations of the occurrence of EMS in families of coho salmon ascending the Platte River. We focused on coho salmon ascending a single river since Wolgamood et al. (2005) had documented among river variation in EMS for Lake Michigan coho salmon. For the purposes of this analysis we reevaluated the relationship between alewife abundance and the occurrence of EMS in families of coho salmon for Lake Michigan using new information.

<table>
<thead>
<tr>
<th>Year</th>
<th>N</th>
<th>Percentage of families affected</th>
<th>Mean EMS (%) in affected families</th>
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<tbody>
<tr>
<td>1999</td>
<td>30</td>
<td>96</td>
<td>100</td>
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<td>2000</td>
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<tr>
<td>2007</td>
<td>24</td>
<td>42</td>
<td>88</td>
</tr>
</tbody>
</table>
we defined EMS as any family having a hatch to feeding fry mortality greater than 20% (Brown et al., 2005c). EMS data are summarised in Table 20.1 and Figure 20.3.

Using a restricted range of ages for alewives (ages one to three) that better reflects those consumed by coho salmon (Madenjian et al. 1998) and constitutes a major portion of the biomass for this species in Lake Michigan (Warner et al. 2009) we found that the occurrence of EMS in coho salmon families was related to alewife biomass by an exponential relationship (\( F=45.4, p<0.01 \); Figure 20.4). The use of a restricted age range and the greater range in biomass of alewives for this time series relative to historic (Figure 20.5), may have increased the likelihood of finding a positive relationship between the occurrence of EMS and alewife biomass that was expected based on earlier observations linking elevated EMS and reduced egg thiamine with alewife consumption (Fitzsimons and Brown, 1998, Honeyfield et al., 2005). The relationship here suggests that during periods of extreme alewife abundance that from the historical record appear to be rare, most coho salmon families may show some level of EMS with corresponding effects on reproduction although these are uncertain since the amount of EMS in a given family does not appear correlated to the proportion of families exhibiting EMS (Wolgamood et al., 2005). During periods of lower alewife abundance it’s evident...
that a greater proportion of coho salmon families would not be expected to show EMS although thiamine deficiency effects on other endpoints for coho salmon are uncertain. Fitzsimons et al. (2009a) noted for larval lake trout that growth was a more sensitive endpoint to the effects of thiamine deficiency than EMS. Nevertheless natural reproduction by coho salmon in Lake Michigan although limited, has been reported for some time (Madenjian et al., 2002). Although the mechanisms involved in limiting the occurrence of EMS among coho salmon families during periods of reduced alewife biomass remain unclear they may involve greater diet diversity as suggested by Brown et al. (2005c). Increased utilization of prey fish in the diet having lower (e.g. rainbow smelt) or no thiaminase (e.g. yellow perch) (Jude et al., 1987; Madenjian et al., 1998b; Tillitt et al., 2005) would conceivably result in a greater uptake of thiamine from the diet.

Future Directions

Attempts at experimentally determining the factors controlling thaminase activity in alewives have yielded few tangible results on the factors controlling thaminase activity in alewives (Lepak et al., 2008; unpublished data). An understanding of controlling factors could potentially be used to develop management actions (e.g. increase lake productivity to affect alewife lipid level) to regulate alewife thaminase activity to a level consistent with natural reproduction by their predators (see Fitzsimons et al., 2007). That such a level exists is suggested by self-sustaining lake trout populations co-existing with alewives in at least two Finger Lakes, although additional mitigating factors may also be involved (Fitzsimons et al., 2007). As a result, other actions may be more appropriate for affecting thaminase intake by predators until a better understanding of factors controlling thaminase activity of particular prey species like alewives becomes available. One such action may be to restore prey diversity to the extent that the relative consumption of thaminase-containing prey fish is considerably reduced and hence does not lead to thiamine deficiency effects in their predators. In some Great Lakes this appears be occurring naturally with the invasion and rapid population increase in the aquatic invasive species round goby (Neogobius melanostoma) (Schaeffer et al., 2005a). This species apparently has low thiaminase activity based on collections in Lake Michigan (Tillitt et al., 2005). In western Lake Ontario after a ten year period during which lake trout
fed almost exclusively on alewives, as many as 20% of lake trout now appear to be consuming gobies based on stomach content analysis (Fitzsimons et al., 2009c). This appears to be sufficient to affect lake trout egg thiamine levels, since average egg thiamine concentrations of lake trout collected during 2007 were almost two-fold higher than in 2003, when gobies were probably absent from the diet (unpublished information). Similarly in Lake Huron, egg thiamine levels in lake trout stocks from the Thunder Bay area that fed almost exclusively on gobies were over twice that of offshore stocks of lake trout that fed almost exclusively on alewives (J. Johnson, MI DNR, and D. Honeyfield, USGS, pers. comm.).

A passive rather than a directed approach to the restoration of the prey fish community to eliminate thiamine deficiency effects may, however, have unintended consequences on the reproductive success of predators. This seems to be the case for gobies and lake trout. Large populations of gobies can have negative consequences for lake trout, as gobies are significant lake trout egg and fry predators (Chotkowski and Marsden, 1999; Fitzsimons et al., 2006). Gobies have been associated with the near elimination of emergence of fry for at least one lake trout spawning reef in Lake Ontario (Fitzsimons et al., 2009c), although additional work is required to determine the spatial extent of lake trout egg and fry predation by gobies in the lake.

Restoration of native species like ciscoes, which lack thiaminase activity, has been advocated (Fitzsimons and O’Gorman, 2006), but impediments to restoration of wild stocks in the Great Lakes are not always clear but as pointed out by Dunlop et al. (2010) may well involve alewives. Accordingly the presence of alewives may make it unlikely that restoration of native prey species like ciscoes would be fully successful. Lake Huron had the lowest abundance of alewives (with the exception of Superior) before alewives crashed there in 2002-2003 yet the abundance of cisco remained low (Dobiesz et al. 2005). It was only after the alewife population crashed in Lake Huron that there has been consistent evidence of spatially and temporally extensive recruitment of cisco in this lake. In contrast, for Lakes Ontario and Michigan, where alewife abundance is much higher, cisco stocks are spatially restricted and show only limited recruitment (J. Hoyle, ON MNR, R. Claramunt, MI DNR, pers. comm.).

Although the complete elimination of alewives from the diet of salmonines may seem like an extreme management action, such a step may be necessary in order to restore normal thiamine nutrition for top predators like lake trout which appear to be more sensitive to the thiamine lowering effects of an alewife diet than Chinook salmon (Fitzsimons et al., 2007). It is not clear how effective restoration of essentially thiaminase-free prey fish would be in restoring thiamine levels in predators if alewives were still present and still being consumed. During the 1980s and 1990s, the prey community of Lake Michigan was dominated by bloater chub (Madenjian et al., 2002) yet lake trout continued to feed as heavily on alewives then as in the 1970s, when bloaters were scarce. This dietary preference was reflected in egg thiamine levels as well (Fitzsimons and Brown, 1998; Honeyfield et al., 2005). In Lake Huron, it was only after a major collapse in alewife stocks occurred (Shaeffer et al., 2005b), forcing lake trout to adopt new diet choices that lacked alewives, that there was a measurable increase in egg thiamine levels (D. Honeyfield, pers comm.; Fitzsimons et al., 2009b). Thiamine levels are now adequate for reproduction, as indicated by increased, spatially extensive and sustained natural reproduction by lake trout in Lake Huron (Riley et al., 2007). Although other factors such as relief from predation of alewives on larval lake trout may also have been involved (see Krueger et al., 1995), Fitzsimons et al. (2009b) concluded that for Lake Huron there was little evidence to support relief from an alewife predation effect as an explanatory variable. These authors found a general lack of overlap between the timing of larval lake trout emergence and onshore migration of alewives. Although changes in lake trout spawner abundance coincident with the decline in alewives may have also contributed to increased lake trout reproduction, these authors found that the spatial and temporal patterns of natural recruits were not consistent with the spatial and temporal patterns of spawner abundance. To support their claim that relief from thiamine deficiency rather than predation may have been a major contributor to the increase in lake trout natural reproduction, Fitzsimons et al. (2009b) documented increases in egg thiamine levels following the crash in the alewife stock and showed that a lake trout fry emergence index (FEI) was positively
correlated with egg thiamine levels, while the occurrence of EMS was negatively correlated with FEI.

**Conclusions**

To conclude, the loss of predator control on clupeids can set off a cascade of events wherein clupeid populations expand, suppress other prey fish species, and eventually become the dominant prey fish (Figure 20.6). In this position, clupeids can dominate predator diets, especially if the abundance of predators has already been depressed by other factors. Depending on their thiaminase activity, which may be under the control of ecosystem factors such as productivity and possibly mediated through the immune system, clupeids can exert a variety of negative impacts at multiple life stages of a predator by the ensuing thiamine deficiency. These negative impacts can culminate in their most extreme case in the virtual elimination of natural reproduction in the predator, possibly leading to population extirpation as appears to have been the case for Lake Ontario and Finger Lakes Atlantic salmon (Ketola et al., 2000). Alternatively a variety of other less extreme scenarios not leading to population extirpation are also possible, depending on the severity of the thiamine deficiency and associated effects although the sustainability of these scenarios remains to be demonstrated.

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References

Chapter 20


References


Fitzsimons, J.D., Brown, S., Brown, L., Honeyfield, D., He, J. and Johnson, J. 2009b. Increase in lake trout reproduction in Lake Huron following the collapse of alewife: Relief from thiamine
deficiency or larval predation? In: Aquatic Ecosystem Health and Management, 13, pp. 1-14.
References


Mather, F. 1881. Fishes that can live in both salt and fresh water. In: Transactions of the American Fisheries Society, 10, pp. 65-75.


Morito, C.L.H., Conrad, D.H. and Hilton, J.W. 1986. The thiamin deficiency signs and requirement of rainbow trout (Salmo gairdneri, Richardson). In: Fish Physiology and Biochemistry, 2, pp. 93-104.
References


References


Chapter 21

Coopperrider, A.Y., Boyd, R.J. and Stuart, H.R. (eds.) 1986. Inventory and monitoring of wildlife habitat. US Dept Inter Bur Land Manage Service Center Denver Co. xviii , 858 pp