RELATIONSHIP BETWEEN DIVING DUCKS AND MUSSEL AQUACULTURE IN PRINCE EDWARD ISLAND, CANADA

By

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B.Sc., Laval University, 2001

A Thesis Submitted in Partial Fulfilment of
the Requirements for the Degree of

Master of Science

In the Graduate Academic Unit of Biology

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THE UNIVERSITY OF NEW BRUNSWICK
August, 2004
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Mussel aquaculture on Prince Edward Island started in the 1970’s, with rapid expansion occurring in the past decade. In recent years, during migration periods, interactions between diving ducks (mainly Greater Scaup and Long-Tailed Duck) and cultivated mussels have increased. Using existing Canadian Wildlife Service duck survey data, I quantified the relationship between ducks and the industry. Diving duck abundance during the fall migration has increased concurrently with mussel landings over the years. Increases in duck numbers took place mainly in areas where mussel aquaculture intensity is high. Ducks are generally size-selective predators when feeding on mussels. I assessed this behaviour by the Greater Scaup in an aquaculture setting, in relation to the shell-mass and shell-crushing minimisation hypotheses. Ducks avoided the larger mussels from the experimental culture site. Results, however, showed support only for the shell-crushing minimisation hypothesis. Finally, I tested a protective socking material, a non-disruptive technique that could prevent duck predation and foster peaceful co-existence between waterfowl and mussel aquaculture. Protective material was ineffective for small mussel seed and only partially effective for medium seed. Conclusions from this study provide strong baseline data for diving duck-aquaculture relationships and practical management strategies to minimise negative impacts of these interactions.
ACKNOWLEDGEMENTS

I am grateful to have been supported by many wonderful people during this intensive research project. This study would not have come to terms without their immense contribution both morally and physically. To all of you I would like to express my deepest and most sincere recognition.

Thank you to all financial and in-kind support that made this project possible, more specially: the University of New Brunswick, AQUANET, the Prince Edward Island Department of Fisheries, Aquaculture and Environment (Robert Thompson, Brian Gillis, Richard Gallant and others members I might have omitted), the P.E.I. Aquaculture Alliance (Crystal McDonald), the Canadian Wildlife Service in Sackville (Keith McAloney and Andrew Hicks), the industry (Stephen Stewart, Robert Fortune, Blaine Thibault and Robert Murphy), the Atlantic Veterinary College (UPEI) and the Mathematics and Statistics Department at UNB (Rolf Turner). Thank you Suzan and James (York Bay Place) for letting us use your quarters in an unfashionable matter.

Special thanks to my numerous field assistants for their blood, sweat and tears. I hope this experience did not discourage you from conducting scientific research, which has changed the face of our earth forever. Thank you Terra May McMullen, Ashley Sprague, Julien Mainguy, Andrea Simmons, Annie Tam, Tara Marshall and Melissa Wong.
I would also like to thank my supervisors and my thesis committee for their guidance, their labour, but most importantly their eternal optimism. Without it, I don’t think I would have hung in there during those tough times. Thank you Diana Hamilton, Myriam Barbeau, Tony Diamond and Greg Robertson. I hope that every graduate student could have the support, commitment and dedication I had.

Last but most importantly I give my greatest appreciation to Jean-Sébastien Lauzon-Guay. I hope you will forgive for being a bit sentimental, but I can’t even imagine going through this without you. Let our paths never go too far apart and our profound friendship continue to grow. Cheers buddy!
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1. General Introduction

In the last twenty years, aquaculture has become a profitable and important food industry in Canada, not only because it is an efficient way of fishing, but also because many of the world’s fisheries have declined and even collapsed. About 47 to 50% of the wild stocks are fully exploited, another 15 to 18% are overexploited and 9 to 10% have been depleted or are recovering from depletion (FAO 2000). The collapse of the Atlantic cod (Gadus morhua) fishery in Eastern Canada during the 1980’s and the early 1990’s forced many fishing communities to change their practices in order to survive. Blue mussel aquaculture (Mytilus edulis) in Prince Edward Island (P.E.I.), Canada started in the 1970’s and expanded greatly following the closure of the cod fishery in 1993. The industry expanded six-fold during the 1990’s, reaching an annual production of 17,000,000 kg in 2000 (Thompson and Gillis 2001). Cultivation of blue mussels has become an important industry in P.E.I., employing 1500 people and contributing $40 million annually to the Island’s economy. Even though P.E.I. is the smallest Province, it produces 80% of Canada’s cultivated mussels.

The implementation of large-scale aquaculture operations in the coastal waters of P.E.I. inevitably changed these habitats, thus affecting the associated wildlife. Cultivation of blue mussels had two main and opposing effects on the Island’s bays: it created a new, stable and abundant food resource, and it increased the level of disturbance with the associated aquaculture activities (e.g., boating).
Like agriculture, aquaculture concentrates large quantities of food, providing an attractive resource for wild animals (Van Vuren and Smallwood, 1996). Interactions between wildlife and human food cultivation activities are numerous and have probably always existed. Examples include deer and geese consuming crops, foxes and weasels stealing poultry, loons and seals foraging at fish farms and diving ducks feeding on cultivated mussels. The first reports of predation by diving ducks on a mussel farm in P.E.I. occurred in 1993.

Many waterfowl species use P.E.I. as a stopover site to feed and build up their fat reserves during the fall and spring migrations. Most species of diving ducks feed naturally on mussels (Goudie and Ankney 1986). In comparison with wild mussels, cultivated mussels are very attractive and have the potential to enhance prey profitability and overall foraging success by ducks for many reasons. They are grown suspended in the water column where conditions are more favourable and as a result, they grow more rapidly than wild mussels. These higher growth rates give cultivated mussels a higher tissue:shell ratio (Dunthorn 1971). Cultivated mussels are also more available, they are found at shallower depths and in higher densities than wild mussels. Finally, cultivated mussels are a less variable resource than wild mussels. They are present from year to year in the same place, and often they have floating structures that allow ducks to locate them. Consequently, there is potential for ducks to profit from this new food source. Food availability and quality can determine body condition in ducks, which in turn is related to overall survival (Haramis et al. 1986)
Aquaculture can also be a very disruptive activity for staging waterfowl. The cultivation of blue mussels is a highly mechanized process that involves intensive boating.

Anthropogenic disturbances can compromise the ability of ducks to acquire the body fat necessary for migration and overwintering survival (Kahl 1991). Fat reserves of a bird during winter become critical, as energy expenditures are high due to thermoregulation costs.

The P.E.I. mussel industry is close to achieving saturation of its suitable areas. Aquaculture lines in some bays use almost 50% of the available surface area (pers. obs.). Waterfowl that normally use these bays as stopover sites during migration can become constrained in terms of habitat use when aquaculture activities are too intensive. In 2002, some 500 Greater Scaup were forced out of a bay during daylight hours for a full month, and they had to pursue their activities in the open water (pers. obs.).

Interactions with diving ducks have increased as the industry expanded, costing $1-2 million annually and threatening the profitability of certain mussel operations (Thompson and Gillis 2001). This conflict is not unique to P.E.I. Reports of severe predation by diving ducks at mussel farms have been confirmed in almost every area where mussels are being cultivated: British Columbia, Eastern Canada, United States, Scotland, Germany, Holland, Norway, etc. (Dunthorn 1971; Glude and Chew 1980; Heritage 1983; Milne and Galbraith 1986; Meixner 1986; Rueggeberg and Booth 1989; Burnett et al. 1994; Thompson and Gillis 2001). Feeding on cultivated mussels appears to be a learned behaviour and deterring it is difficult (Burnett et al. 1994). Waterfowl, in
general, also show strong site tenacity, leading them to return year after year to the same staging sites (Robertson and Cooke 1999), exacerbating the problem.

In P.E.I., the arrival of the majority of the ducks (October, November) coincides with socking of mussels. Growers collect mussels from spat lines, then transfer them into plastic mesh socks (socking) where they are grown, suspended in the water column, until they reach commercial size. It is during this initial period, when the mussels are small, that the majority of losses are recorded. Ducks swallow the mussels whole and are typically size-selective, preferring the smaller prey (Draulans 1982, 1984; Nyström and Pehrsson 1988; Bustnes and Erikstad 1990; Guillemette 1994; De Leeuw 1999; Hamilton et al. 1999). Mussels remain vulnerable because of their small size until the bays freeze up (late December). Mussels do not grow much during winter and they become available again during the spring, as the ice clears away. There have been reports of predation by diving ducks during the spring staging period, but not to the extent experienced during fall. Numbers of birds do not build up as much and they do not remain in the area as long during the spring staging period.

In order to reduce losses, mussel growers have used several scaring techniques, all with limited success. Visual deterrents (e.g., scarecrows) resulted in rapid habituation by the birds. Acoustic deterrents like propane canons achieved similar results, as well as creating noise pollution for surrounding residents. The most effective technique used in P.E.I. to date consists of all-day boat chasing reinforced with starter pistols. However, this technique is very expensive and protects the crop during daylight hours only. Some diving ducks species also feed at night (McNeil et al. 1992; Systad et al. 200). During
fall 2001, $100,000 worth of mussels was lost to Greater Scaup in three to four nights (R. Murphy pers. comm.). Therefore, new and less disruptive deterrents that offer 24-hour protection are needed to foster peaceful co-existence between diving ducks and mussel growers.

Long-Tailed Duck (Clangula hyemalis) and Greater Scaup (Aythya marila) have been identified as the most problematic waterfowl species for mussel aquaculture in P.E.I. during the fall staging period. Long-Tailed Duck are sea ducks, which normally stage in open water (Bellrose 1980). Growers have reported more and more Long-Tailed Duck leaving their traditional feeding areas to forage on mussel farms in the sheltered bays. They usually form small groups of no more than 20, and play a cat and mouse game with the different boats during the day, then return to the open water to spend the night.

Greater Scaup, on the other hand, are bay ducks, which usually stage in sheltered waters (Austin et al. 1998), such as those in P.E.I. bays where mussels are cultivated. Scaup tend to aggregate in higher numbers than Long-Tailed Duck, making them easier to scare during the day. However scaup, unlike Long-Tailed Duck, also feed at night (Nilsson 1970; Thornburg 1973; Custer et al. 1996).

Although both species could benefit from the cultivated mussels, the disturbance associated with aquaculture could also have adverse effects on duck populations, especially for species like the Greater Scaup that share the same habitat. Studying the effects of aquaculture on waterfowl populations is critical, as 10 of the 15 species of North American sea duck species are in a continental decline (Sea Duck Joint Venture
Management Board 2001). Scaup populations are also in a continental decline; numbers have decreased dramatically since the early 1980’s (Austin et al. 2000).

As aquaculture expands all over the world, so will the interactions with waterfowl. Studies are needed to evaluate the impact of aquaculture on ducks, but also to understand and reduce predation on cultivated mussels. Aquaculture represents an important economic activity, so research is also needed to promote a more sustainable development of the industry.

1.1. Objectives, hypotheses and research questions

The main objectives of this industry partnership research were to quantify the relationship between diving duck numbers and the intensity of mussel aquaculture, to study the foraging behaviour of the Greater Scaup on mussel farms, and to test a protective socking material against duck predation.

In the first part of this study, I examined the relationship between the abundance and distribution of the two main diving duck species during the fall staging period in response to the development of mussel aquaculture in P.E.I. If food resources can regulate waterfowl abundance and distribution (Milne 1969; Pehrsson 1984; Van Eerden 1984; Stanczyskowska et al. 1990; Wormington and Leach 1992; Gardarsson and Einarsson 1994; Larsen and Guillemette 2000), then the development of mussel aquaculture is expected to affect the abundance and distribution of Greater Scaup and Long-Tailed Duck during the fall. To answer this question, I analysed existing aerial
survey data from the Canadian Wildlife Service (CWS) on the historical numbers and distribution of the two ducks species in relation to the development and the intensity of mussel aquaculture.

In the second part, I studied the size-selective behaviour of the Greater Scaup when feeding on cultivated mussels. The purpose was to quantify losses on the different mussel seed sizes used by growers, as well to test two hypotheses proposed to explain why diving ducks select small mussels. A prey-choice experiment was conducted using mussel culture sites, and results were analysed in relation to the shell-mass minimisation and the shell-crushing minimisation hypotheses. If the dry tissue:shell ratio decreases, as mussels get larger, then ducks should select the smallest prey (Bustnes and Erikstad 1990; Bustnes 1998; Hamilton et al. 1999), supporting the shell-mass minimization hypothesis. If the work needed to crush mussel shells increases, as mussels get bigger, then ducks should select the smallest prey (De Leeuw and Van Eerden 1992; Hamilton et al. 1999), supporting the shell-crushing minimization hypothesis.

Finally, I tested the efficacy of a protective socking material to prevent predation by diving ducks. This non-disruptive deterrent was proposed by the industry. My objective was to determine whether the protective material reduced losses for the different mussel seed sizes used by growers. An experiment was carried out on mussel culture sites using protected and unprotected mussel socks. If the protective material is an effective deterrent against predation by diving ducks, then losses of the different mussel seed sizes will be significantly greater for mussels socked in the regular material compared
with the protective one. The protective socking represents a potential non-disruptive
deterrent that offers 24-hour protection against predation by diving ducks.

I conclude this thesis with a general conclusion that highlights the major findings of this
research and offer practical management techniques that could help avoid or reduce the
severity of interactions between diving ducks and mussel aquaculture in P.E.I.

The thesis is presented in an article format for future publication. Each chapter contains
a title page with authorship and the journal to which the article will be submitted. Diana
J. Hamilton obtained co-authorship in every Chapter for her intellectual contributions in
the statistical design of the experiments, analysis of the results and editing. Antony W.
Diamond obtained co-authorship in Chapter 2 and 3 for his intellectual contributions in
the analysis of the results and editing. Jean-Sébastien Lauzon-Gauy obtained co-
authorship for his field assistance and intellectual contributions in Chapter 3, and for
data collection, analysis and writing in Chapter 4. Finally, Myriam A. Barbeau obtained
co-authorship in Chapter 4 for her intellectual contributions in the statistical design and
analysis of the experiment.

1.2. Bibliography

Austin, J.E., C.M. Custer and G.E. Allen, 1998. Lesser Scaup (Aythya affinis). In The
Birds of North America. Edited by Poole, A.A. and E. Gill. 338. The American
Ornithologists’ Union, Philadelphia, Washington, D.C., U.S.A.


Meixner, R. 1986. The predation of mussels by eiders (*Somateria mollissima*) and its effect on German mussel farming. Ices Council meeting 1986 (collected papers), Ices, Copenhagen (Denmark), 3 pp.


Relationship between abundance of Greater Scaup (*Aythya marila*) and Long-Tailed Duck (*Clangula hyemalis*) and cultivated mussels during the fall staging period in Prince Edward Island, Canada.

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Abstract

Blue mussel (*Mytilus edulis*) aquaculture on Prince Edward Island started in the 1970’s, with rapid expansion occurring in the past decade. In recent years, during migration periods, interactions between diving ducks (mainly Greater Scaup and Long-Tailed Duck) and cultivated mussels have increased. Using existing Canadian Wildlife Survey duck survey data, I quantified the relationship between ducks and the industry. Diving duck abundance during the fall migration has increased concurrently with mussel landings over the years. Increases in duck numbers took place mainly in areas where mussel aquaculture intensity is high. Greater Scaup did not redistribute, as they were most abundant in those areas prior to the presence of cultivated mussels. On the other hand, historical numbers of Long-Tailed Duck were consistent in all areas; suggesting that they redistributed according to the level of mussel aquaculture.

Journal to which article will be submitted: *Journal of Wildlife Management*
2. Relationship between abundance of Greater Scaup (*Aythya marila*) and Long-Tailed Duck (*Clangula hyemalis*) and cultivated mussels during the fall staging period in Prince Edward Island, Canada.

2.1. Introduction

Many studies have shown that food resources can regulate waterfowl abundance and distribution (Milne 1969; Pehrsson 1984; Van Eerden 1984; Stanczyskowska *et al.* 1990; Wormington and Leach 1992; Gardarsson and Einarsson 1994; Larsen and Guillemette 2000). Nutrition can play a crucial role in many stages of a duck’s life cycle, including reproduction, moulting, migration and the overwintering period. Food resources are especially important for brood survival, which in turn can determine the species’ productivity (Hill 1984; Holmes *et al.* 1991; Gardarsson and Einarsson 1994). In order for ducks to reproduce successfully, they must acquire sufficient food for egg production, incubation and caring for ducklings (Meijer and Drent 1999). Food can be acquired before arriving at the nesting grounds (income breeders) or at the nesting ground (capital breeders). First year birds are very sensitive to food depletion because of their reduced ability to forage (Goss-Custard *et al.* 1982; Goss-Custard and Dit Durell 1987). Young birds may be less efficient at finding food because of their lack of experience and competition with older birds. This can become critical when young ducks are exposed to harsh conditions during their first wintering period, when energy expenditures are high. A combination of food depletion and harsh winters can also be
detrimental to the condition of mature waterfowl, possibly reducing their reproductive output (Oosterhuis and Van Dijk 2002) and recruitment, thereby affecting the population’s status (Gardarsson and Einnarsson 1994).

There are many examples of new and abundant food sources having dramatic effects on waterfowl abundance, distribution and behaviour. Such is the case with the highly successful and invasive zebra mussel (*Dreissena polymorpha*), which has colonized many parts of Western Europe and North America. In Switzerland, the invasion led to an increase in the duck population using Lake Neuchatêl during winter (Pedroli 1981). Birds have altered their migration patterns to feed on zebra mussels in newly colonized areas (Geroudet 1966; Pedroli 1981, 1982). Zebra mussels were introduced in Lake Erie and Lake Ontario in 1985 and 1986, respectively (Griffiths *et al.* 1991). In 1988, a strong increase and shift in location of waterfowl was observed relative to this novel food source (Wormington and Leach 1992). Ducks feeding in the Great Lakes now routinely feed on zebra mussels (Hamilton and Ankney 1994; Custer and Custer 1996) and many species consume them almost exclusively (Mitchell and Bailey 2000).

Human activities can have a significant impact on waterfowl habitat, and consequently affect foraging and survival. Examples include agriculture and aquaculture, which have increased food availability for many birds but also the amount of disturbance to which the birds are exposed. Disturbance can influence a bird’s ability to acquire the necessary nutrients for the different stages of its life cycle (Knapton *et al.* 2000). Costs and benefits are therefore associated with these kinds of interactions, and effects can vary depending on the specific parameters of the interactions.
With the decline of wild fisheries in the past two decades (FAO 2000), aquaculture has become a profitable and indispensable food industry. Experimental mussel aquaculture on long-lines started at Linne Mhuirich, Scotland, in 1966. By 1968, when commercial operations began, there were reports of depredation by Common Eiders (*Somateria mollissima*) (Dunthorn 1971). The abundance of eiders in that region increased with successive years of cultivation (Milne and Galbraith 1986). Similar interactions between diving ducks and cultivated mussels have been reported elsewhere. In Germany, numbers of eiders feeding at mussel farms doubled between 1979-80 and 1984-86 and growers experienced serious losses due to eider predation (Meixner 1986). Sea ducks have also been identified as a major problem in Canada, the United States, Holland and Norway (Glude and Chew 1980; Heritage 1983). Scoters (*Melanitta* spp.) have been identified as the principal cause of losses in British Columbia, and reports of predation by these ducks occurred rapidly after suspended mussel culture techniques were initiated (Rueggeberg and Booth 1989). The east coast of Canada is also not immune to these phenomena; depredation issues have grown as the industry has expanded.

Although mussels are an important part of most diving ducks’ diets (Goudie and Ankney 1986), feeding on cultivated mussels appears to be a learned behaviour and deterring it is difficult (Burnett *et al.* 1994). Specialized diets and shifts in food selection can accompany changes in food availability and density (Goudie and Ankney 1986; Bairlein 1990). Cultivated mussels have provided for many birds a new, abundant and high quality food resource that reduces searching and foraging time. Natural mussel beds are often characterized by variable recruitment and high levels of mortality (Larsen and
Guillemette 2000), which makes them variable in time, location and quality. Conversely, cultured mussels are present from year to year at the same place, and floating structures associated with culture techniques make it easier for birds to locate the resource. Conflicts with ducks arise because cultivated mussels are often grown in areas that overlap with breeding, staging and wintering habitat of waterfowl that naturally feed on mussels.

Increasing interactions between diving ducks and cultivated mussels have been reported in Prince Edward Island (P.E.I.), Canada. Diving ducks, mainly Greater Scaup (*Aythya marila*) and Long-Tailed Duck (*Clangula hyemalis*), that stage in this area during fall and spring migration, have responded to this new and abundant food resource. Mussel aquaculture in P.E.I. started in 1970, and the industry expanded six fold during the 1990’s, reaching an annual mussel production of around 17,000,000 kg in 2000 (Thompson and Gillis 2001). As is the case with previous examples, ducks seem to have responded to this new food resource with changes in their abundance.

The purpose of this study was to investigate the relationship between abundance of Greater Scaup and Long-Tailed Duck and cultivated mussels on P.E.I. Using existing Canadian Wildlife Service survey data and mussel landings provided by the Department of Fisheries and Oceans, I wished to determine whether an increase in duck abundance has occurred, and whether the distribution of migrating waterfowl has changed in response to the increase in mussel aquaculture in P.E.I. Although diving duck populations could benefit from this high quality resource, scaring tactics used by mussel growers could be detrimental to them. Studying the effects of aquaculture on waterfowl
populations is important, as 10 of the 15 species of North American sea duck species are in a continental decline (Sea Duck Joint Venture Management Board 2001) and aquaculture is expected to increase in the future, therefore increasing the potential for interactions. Results of this study may help to foreshadow the response of ducks to expanding mussel aquaculture in other areas.

2.2. Materials and methods

2.2.1. Aerial survey techniques

Aerial surveys of staging and wintering waterfowl in Prince Edward Island (P.E.I.) Canada started in 1966 following standard Canadian Wildlife Service (CWS) techniques, although surveys were not carried out every year (see Table 2.1 for details). Surveys were flown in a Cessna 172 (single engine, high wing profile) once monthly from late September or October to December or early January. Waterfowl habitats were surveyed at approximately 70 m above ground level where possible. Populated areas required a higher altitude for safety reasons. The Island was divided into survey blocks including the coastline and extended approximately 250 m out from shore (Figure 2.1). Waterfowl abundance was established using the average count of the two observers, Survey area, frequency and dates varied during the 36-year period due to funding and weather conditions. From 1966 to 1988, all survey blocks (35 blocks) were monitored. After this period, only coastal blocks from the northern and eastern shores were surveyed (blocks 383 to 390, 393 to 398 and 402 to 408). Data from the northern and
eastern blocks, collected in October through December each year, were used in this analysis.

2.2.2. Mussel landings

Data on mussel landings for P.E.I. were compiled and provided by the Department of Fisheries and Ocean Canada (DFO) from their Policy and Economics Branch in the Gulf Region. Data represent total cultured mussel landings per year. Reported landings started in 1980.

2.2.3. Data analysis

All statistical analyses were carried out using SAS Institute software package version 8.2. Significance level (alpha) for main effects and interaction was set to 0.05 and 0.01, respectively. The relationship between total duck abundance per year (dependent variable) and total cultured mussel landings per year (independent variable) was assessed using regression. Total duck abundance was calculated using CWS survey data during the fall staging period. Existing data from October, November and December were averaged to estimate total duck abundance. The number of surveys used to establish total duck abundance served as a weight variable in the model. Waterfowl survey years (n=10) prior to initiation of mussel aquaculture were pooled into one data point to avoid an
Table 2.1 Details of aerial surveys conducted by Canadian Wildlife Service between 1966 and 2002 on Prince Edward Island, Canada.

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<td>2002</td>
<td>5 Dec</td>
<td>North &amp; East**</td>
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*All: includes all 35 survey blocks

**North & East: Includes 21 survey blocks (blocks 383 to 390, 393 to 398 and 402 to 408)
**Figure 2.1** Canadian Wildlife Service aerial survey block map for Prince Edward Island, Canada.
excessive number of zeros for mussel landings. Homogeneity of variance and independence of data were verified by visual inspection of the residuals against predicted values plot and an index plot, respectively. Greater Scaup and Long-tailed Duck numbers were analysed separately.

To determine whether temporal changes in duck populations varied with the level of mussel aquaculture, an analysis of covariance (ANCOVA) was used. Aerial blocks surveyed for duck abundance were divided into three levels of aquaculture (Low or none, Medium and High), defined on the next page. Mean duck abundance during fall was the dependent variable, year of survey the independent variable and level of aquaculture the class variable. Survey years prior to mussel aquaculture were not pooled in this analysis. Mean duck abundance was calculated by dividing total duck abundance for each level of aquaculture by the number of blocks in that level. Mean duck abundance was log_{10} (Y + 1) transformed to meet the assumption of homogeneity of variance among areas with different levels of aquaculture. Number of surveys used to establish total duck abundance served as a weight variable in the model. Another class variable (Total ducks) was created and used as a random effect in the model to account for inter-annual variation on total island abundance unrelated to aquaculture. Total abundance ducks was divided into three categories (High, Medium and Low duck years). A high duck year was used when total island abundance was over 1000 individuals, medium when it ranged between 500 and 1000 birds and a low duck year was scored when total abundance was less than 500 ducks. Greater Scaup and Long-Tailed Duck numbers were analysed separately. Long-tailed Duck abundance models were determined to be linear and Greater Scaup quadratic, based on residuals and
significance of the models. Interactions between year of survey squared and level of aquaculture were tested to determine if a different quadratic term was needed in the Greater Scaup models. When significant interactions between year of survey and level of aquaculture were found, individual regressions with untransformed data for areas with different aquaculture intensity were used to pursue the analysis. Again, the number of observations used to establish mean abundance of duck served as a weight variable in the model. Homogeneity of variance and independence of data were checked by visual inspection of the residuals against predicted values plot and an index plot, respectively.

The variable "level of aquaculture" was determined using mean annual mussel landings from the last five years (1998-2002). Low aquaculture zones each had less than 1,600 kg of landed mussels per year and encompassed seven blocks. Medium aquaculture zones had an annual production of mussels ranging between 1,600 and 700,000 kg in each of six blocks. Areas with high aquaculture activities landed over 700,000 kg annually and comprised nine blocks. Landings in the different levels of aquaculture were compared using an unbalanced one-way analysis of variance (ANOVA) with planned comparisons (High vs. Medium and Medium vs. Low or none). Landings per block were log_{10} (Y+1) transformed to satisfy Levene’s homogeneity of variance test.

To assess the possibility that variation in duck abundance among levels of aquaculture was actually an artefact of differences in block area among high, medium, and low aquaculture zones, two separate analyses were carried out. First, survey block surface areas for the different levels of aquaculture were compared with an unbalanced one-way ANOVA. Homogeneity of variance was verified using a Levene’s test. Second,
surveys were divided into three aquaculture periods (Pre, Early and Late) and mean duck abundances within each period were regressed against the surface area of the survey blocks. Mean duck abundance was calculated by dividing total duck abundance in a block by the number of years where a survey was conducted during the aquaculture period. Pre, Early and Late aquaculture period correspond to 1966-79 \( (n = 11) \), 1980-95 \( (n = 4) \) and 1996-2002 \( (n = 5) \) of the survey period respectively, with \( n \) representing the number of years where a survey was conducted. Aquaculture periods were defined following major increases in annual landings. Survey block surface area was estimated from the Canadian Wildlife Service aerial survey block map for P.E.I. (Figure 2.1), using Image Pro Plus software version 8.0.

2.3. Results

2.3.1. Results of CWS aerial surveys and DFO mussel landings in P.E.I.

Fall abundance of Greater Scaup and Long-Tailed Duck in P.E.I. showed considerable variation through the 36-year period (Figure 2.2). Greater Scaup abundance declined from 1966 to 1987, but then increased to reach peak numbers in 2002 with 2020 individuals. On the other hand, numbers of Long-Tailed Duck generally increased from 1967 to 1982, plummeted to 79 individuals in 1987, and then increased again to a maximum of 1294 ducks in 2000.
Figure 2.2 Total abundance of two duck species (Greater Scaup and Long-Tailed Duck) and cultured mussel landings over time. Aerial survey data collected by the Canadian Wildlife Service during the fall staging period (October, November and December) were averaged to estimate total duck abundance. Mussel landings were total annual harvest recorded by the Department of Fisheries and Oceans Canada.
Mussel aquaculture in P.E.I. has greatly expanded from its beginning in 1980 up to the present day (Figure 2.2). Landings per year increased rapidly in time with three major periods, 1980 to 1988, 1989 to 1995 and 1996 to 2002. Mussel harvest reached a record weight of 17,218,904 kg in 2000 and then declined slightly, with growers having attained maximum capacities from their aquaculture leases. Establishment of new aquaculture leases for mussels has slowed considerably in recent years. Suitable new areas for mussel aquaculture have become sparse and lease applications now have to go through environmental impact assessment, which requires more time.

2.3.2. Relationship between duck abundance and mussel landings

The numbers of Greater Scaup using P.E.I. as a staging ground during fall migration have increased linearly with landed cultured mussels per year (Figure 2.3; DF= 1, 8, F= 30.15, \( R^2 = 0.7903 \), p= 0.0006). Although mussel landings from one year inevitably influence landings of the next, index plot revealed no evidence of serial correlation. Similar results were obtained when total duck abundance was plotted against years, because the quadratic relationship between mussel landings and years was very tight (DF= 2, 21, F= 193.74, \( R^2 = 0.9486 \), p < 0.0001).
**Figure 2.3** Linear regression with 95% confidence intervals of total abundance of Greater Scaup on mussel landings \((Y = 293.56 + 8.7 \times 10^{-5} X)\). Aerial survey data collected by the Canadian Wildlife Service during the fall staging period (October, November and December) were averaged to estimate total duck abundance. Mussel landings were total annual harvest recorded by the Department of Fisheries and Oceans Canada.
The abundance of Long-Tailed Duck in P.E.I. during the fall staging period also increased linearly with landed cultured mussels per year, but the relationship was not as strong and significant as with Greater Scaup (Figure 2.4; DF= 1, 8,  F= 5.32,  R² = 0.3993,  p = 0.05). Index plot revealed no problems of serial dependency among mussel landing data points. Once again, when abundance of Long-Tailed Duck was plotted against years, similar results were obtained because of the tight relationship between mussel landings and years.
Figure 2.4 Linear regression with 95% confidence intervals of total abundance of Long-Tailed Duck and mussel landings ($Y = 369.06 + 3.9 \times 10^{-5} X$). Aerial survey data collected by the Canadian Wildlife Service during the fall staging period (October, November and December) were averaged to estimate total duck abundance. Mussel landings were total annual harvest recorded by the Department of Fisheries and Oceans Canada.
### 2.3.3. Relationship between ducks distribution and intensity of mussel aquaculture

Abundance of Greater Scaup over time differed between areas with low, medium and high level of mussel aquaculture (Table 2.2; ANCOVA, interaction between years and aquaculture level). When the model was run with an interaction between Years*Years and aquaculture level, it showed no evidence that a different quadratic term across aquaculture levels was needed (DF= 2, 48 F= 0.22, \( p = 0.8047 \)).

Mean number of Greater Scaup per block in areas where mussel aquaculture was low or nonexistent has been close to nil over the 36 years survey period (Figure 2.5 Low). The model was non-significant under an alpha level of 0.05 (DF= 2, 16, \( F=3.11, \ R^2 = 0.2797, \ p = 0.0724 \)). Visual inspection of the residuals revealed that data violated assumptions of homogeneity of variance and absence of serial correlation. No transformation could resolve the violated assumptions. Although the statistical analysis is suspect because of violations of assumption, the data clearly show that there is no trend in mean scaup abundance per block over time. Ducks were observed on only two occasions during the survey period, 1968 and 1970.

In areas with medium levels of mussel aquaculture, Greater Scaup were present in the early part of the survey period, reaching a maximum mean of 14 individuals per block in 1968, but then were not seen again until 1995. Numbers seemed to increase again but they never exceeded 4 birds, resulting in a curvilinear relationship (Figure 2.5 Medium) that was barely significant (DF= 2, 16, \( F= 3.64, \ R^2 = 0.3128, \ p = 0.0497 \)). The model
failed to meet the assumptions of homogeneity of the variance and absence of serial correlation. No transformation \( \log_{10}, \ln \) and square root) could resolve the violated assumptions. Statistical results are therefore questionable. However, as for the low aquaculture areas, there was no clear trend in scaup abundance over time.

Areas with high aquaculture levels harboured most of the Greater Scaup during the survey period (Figure 2.5, High). Mean abundance per block seemed to decline from 1966 to 1987, from 161 to 5 ducks respectively. Greater Scaup then increased to reach a peak of 195 individuals per block in 2002. The model was significant (DF= 2, 16, \( F= 23.42, \) \( R^2 = 0.7454, \) \( p < 0.0001 \)) and did not violate the homogeneity of variance and independence of data assumptions.
Table 2.2 Results of an ANCOVA with log\(_{10}\) (mean Greater Scaup abundance per block +1) (Logducks) as the dependant variable, Years as the covariate, and aquaculture level as the class variable. Total ducks represents a class variable that divided total island Greater Scaup abundance per year into three categories (Low, Medium and High duck year). Total ducks is used as a random effect in the model. The type I sum of squares (SS) was used because of the random effect in the model which is model-order dependent.

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<th>P</th>
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Figure 2.5 Quadratic regressions with 95% confidence intervals of Greater Scaup mean abundance per block over time for areas with different levels of mussel aquaculture (low, medium and high) (high: $Y = 79.56 - 10.621 X + 0.35 X^2$).
Abundance of Long-Tailed Duck over time differed among areas with low, medium and high levels of mussel aquaculture (Table 2.3; ANCOVA, interaction between years and aquaculture level).

Mean Long-Tailed Duck abundance per block in areas with low levels of mussel aquaculture changed very little during the course of the survey and showed no clear trend over time (Figure 2.6 Low; DF= 1, 16, F= 0.35, R² = 0.0217, p = 0.5601). With the exception of 1982, when abundance reached 89 individuals, the population was fairly stable and no ducks were observed on many occasions. Underlying assumptions of homogeneity of variance and independence of data were met. One outlier was found, but the model remained non-significant when it was removed.

The mean number of Long-Tailed Ducks per block staging in areas with medium levels of aquaculture generally increased during the 35-year period (Figure 2.6 Medium; DF= 1, 16, F= 6.79, R² = 0.2980, p = 0.0191). Duck populations in these areas peaked at 60 birds in 1998. Inspection of the residuals showed no violation of the homogeneity of variance and independence of data assumptions.

Long-Tailed Duck population in areas with high levels of mussel aquaculture appeared higher than in other areas (Figure 2.6, High). Mean abundance per block increased with time (DF= 1, 16, F= 8.99, R² = 0.3599, p = 0.0085), reaching a maximum of 91 birds in 1998. Inspection of the residuals showed that the model met the homogeneity of variance and independence of data assumptions.
Table 2.3 Results of an ANCOVA with $\log_{10}$ (mean Long-Tailed Duck abundance per block +1) (Logducks) as the dependant variable, Years as the covariate, and aquaculture level as the class variable. Total ducks represents a class variable that divided total island Long-Tailed Duck abundance per year into three categories (Low, Medium and High duck year). Total ducks is used as a random effect in the model. The type I sum of squares (SS) was used because of the random effect in the model which is model-order dependent.

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<td>26.595</td>
<td>3.799</td>
<td>7.08</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Error</td>
<td>46</td>
<td>24.674</td>
<td>0.536</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>53</td>
<td>51.269</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R-Square Coefficient of Variation Root MSE Logducks Mean
0.519 79.695 0.732 0.919

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Type I SS</th>
<th>Mean Square</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>aquaculture level</td>
<td>2</td>
<td>7.978</td>
<td>3.989</td>
<td>7.44</td>
<td>0.0016</td>
</tr>
<tr>
<td>Years</td>
<td>1</td>
<td>3.257</td>
<td>3.257</td>
<td>6.07</td>
<td>0.0175</td>
</tr>
<tr>
<td>Years*aquaculture level</td>
<td>2</td>
<td>7.575</td>
<td>3.788</td>
<td>7.06</td>
<td>0.0021</td>
</tr>
<tr>
<td>Total ducks</td>
<td>2</td>
<td>7.785</td>
<td>3.892</td>
<td>7.26</td>
<td>0.0018</td>
</tr>
</tbody>
</table>
Figure 2.6 Linear regressions with 95% confidence intervals of mean abundance of Long-Tailed Duck over time for areas with different levels of mussel aquaculture (low, medium and high) (high: $Y = -2.95 + 1.51 X$, medium: $Y = 0.34 + 1.69 X$).
Mean Long-Tailed Duck abundance per block

Years

Low

Medium

High
2.3.4. *Landings and the level of aquaculture*

Mean mussel landings differed among levels of aquaculture (DF= 2, 18, F= 119.67, p < 0.0001). Planned comparisons revealed that mussel landings in high aquaculture zones were higher than landings in medium aquaculture zones (DF= 1, 18, F= 4.46, p = 0.0488). Landings in areas with low or no aquaculture were also significantly lower than in areas with medium level of aquaculture (DF= 1, 18, F= 117.12, p < 0.0001).

2.3.5. *Area effect on duck abundance*

Survey block surface area did not differ significantly among zones with different levels of aquaculture (Table 2.4). However, power analysis revealed that there was less than 10% chance of detecting a true difference between areas with different levels of aquaculture (α = 0.05). Difference between means compared was used as the minimal detectable difference. It is therefore difficult to say whether or not the different zones had different size blocks. No relationship was found between mean abundance of Greater Scaup and Long-Tailed Duck over survey block surface area during any of the three aquaculture periods. All regressions yielded non-significant results (Table 2.5).
Table 2.4 Results of an unbalanced one-way ANOVA of the survey block surface area in the different levels of aquaculture (aquaculture level).

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean square</th>
<th>F</th>
<th>p</th>
</tr>
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<tr>
<td>aquaculture level</td>
<td>2</td>
<td>2849.140</td>
<td>1424.570</td>
<td>2.27</td>
<td>0.1316</td>
</tr>
<tr>
<td>Error</td>
<td>18</td>
<td>11273.748</td>
<td>626.319</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>20</td>
<td>14122.888</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>aquaculture level</th>
<th>n</th>
<th>Mean (Km²)</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low or none</td>
<td>7</td>
<td>11.42</td>
<td>4.19</td>
</tr>
<tr>
<td>Medium</td>
<td>5</td>
<td>13.05</td>
<td>5.21</td>
</tr>
<tr>
<td>High</td>
<td>9</td>
<td>35.60</td>
<td>11.78</td>
</tr>
</tbody>
</table>

Table 2.5 Statistics associated with linear regression models for Greater Scaup and Long-Tailed Duck mean abundance over survey block surface area, during three aquaculture periods (Pre, Early and Late).

<table>
<thead>
<tr>
<th>Aquaculture period</th>
<th>DF</th>
<th>F</th>
<th>R²</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greater Scaup</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre (1966-79)</td>
<td>1,19</td>
<td>2.58</td>
<td>0.1196</td>
<td>0.1246</td>
</tr>
<tr>
<td>Early (1980-95)</td>
<td>1,19</td>
<td>0.01</td>
<td>0.0007</td>
<td>0.9063</td>
</tr>
<tr>
<td>Late (1996-2002)</td>
<td>1,19</td>
<td>2.33</td>
<td>0.1092</td>
<td>0.1434</td>
</tr>
<tr>
<td>Long-Tailed Duck</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre (1966-79)</td>
<td>1,19</td>
<td>0.28</td>
<td>0.0145</td>
<td>0.6027</td>
</tr>
<tr>
<td>Early (1980-95)</td>
<td>1,19</td>
<td>0.1</td>
<td>0.0052</td>
<td>0.3128</td>
</tr>
<tr>
<td>Late (1996-2002)</td>
<td>1,19</td>
<td>1.08</td>
<td>0.0536</td>
<td>0.7566</td>
</tr>
</tbody>
</table>
2.4. Discussion

2.4.1. Relationship between duck abundance and cultured mussels

Cultivated mussels provide an attractive target for foraging ducks. They are an abundant food resource that is present from year to year and the associated floating structure can also make it easier for birds to locate the resource, compared with wild mussels. Cultivated mussels are grown suspended in the water column and growth rates are higher than wild mussels (Dunthorn 1971). This higher growth rate apparently increases the dry tissue to shell weight ratio compared with wild mussels, which would make feeding on cultivated mussels more energetically profitable. As a result, duck abundance is thought to be influenced by mussel aquaculture.

The number of Greater Scaup using P.E.I. as a staging area during fall migration showed considerable variation prior to aquaculture, but seemed to decline until 1982. Abundance generally increased afterward, following the expansion of the mussel industry characterized by an increase in the quantity of landed mussels. A plausible explanation for the increase of Greater Scaup in P.E.I. is that mussel aquaculture provides ducks with an abundant and highly profitable food source. Food availability can determine body condition, which in turn relates to overall survival (Haramis et al. 1986). This may also be beneficial for recruitment, especially for first year birds, which have a higher mortality rate than adults during winter, possibly due to their reduced ability to forage (Goss Custard et al. 1982; Goss-Custard and Dit Durell 1987). Spring staging in this area, which appears to be on the rise (R. G. Thompson, pers comm.) could also have
benefited sexually mature ducks returning to breeding grounds. Ducks must acquire sufficient energy in order to reproduce, and birds with higher energy reserves have a better chance of rearing more ducklings (Meijer and Drent 1999). Cultured mussels could provide ample nutrition to increase fat reserves for breeders.

Although the rise in Greater Scaup abundance could be associated with a higher breeding success, scaup numbers in North America have declined dramatically since the early 1980’s (Austin et al. 2000). However, Greater Scaup and Lesser Scaup were not counted separately during those surveys and it is estimated that Lesser Scaup constitute 89% of the continental scaup population (Austin et al. 2000), while Greater Scaup represent 95% of the fall staging scaup population on P.E.I. (pers. obs.). Therefore, the actual status of Greater Scaup in North America remains unclear, and future continental surveys should attempt to distinguish Lesser and Greater Scaup to address the continental status of Greater Scaup.

Long-Tailed Duck populations staging in P.E.I. during the fall migration generally increased from 1967 to 1982, then plunged in 1987. Abundance increased again following expansion of mussel aquaculture. This increase does not reflect broader population trends; the status of Long-Tailed Duck in eastern North America appears to be stable, but estimates could be erroneous since there are no eastern breeding population surveys (Sea Duck Joint Venture Management Board 2001).

Long-Tailed Ducks have an extremely varied diet, but mobile crustaceans (primarily amphipods) are normally their most dominant prey (Roberston and Savard 2002).
Feeding on high density sessile mussels could reduce costs associated with foraging (searching and chasing), compared with amphipods, making mussels a profitable prey. Consequently, it is possible that cultivated mussels have drawn more and more Long-Tailed Duck away from traditional feeding grounds with successive years of cultivation. In Europe, Tufted Ducks (*Aythya fuligula*) and Pochards (*A. farina*) altered their migration patterns and shifted their staging location in response to the zebra mussel invasion (Geroudet 1966; Pedroli 1981, 1982). The same behaviour was also observed in North America with Lesser Scaup (*A. affinis*) and Canvasback (*A. valisineria*) (Wormington and Leach 1992; Hamilton and Ankney 1994). However, these results should be considered with caution due to the nature of the aerial surveys relative to typical habitat for Long-Tailed Duck. The northern and eastern coasts of P.E.I. are characterized by long shallow sandy beaches and, contrary to Greater Scaup, which prefer sheltered bays in P.E.I. (pers. obs.), Long-Tailed Duck typically feed farther offshore in deeper waters (Bellrose 1980). Aerial blocks flown during surveys include an offshore section that extends only to about 250 m, and so might not encompass all Long-Tailed Duck habitat around the island. Results could therefore reflect more a change in the choice of foraging area rather than a change in abundance.

2.4.2. *Relationship between duck distributions and cultured mussels*

Historical numbers of Greater Scaup in areas that eventually harboured low and medium levels of mussel aquaculture were low or non-existent compared with areas containing high aquaculture activities. Therefore, ducks did not redistribute according to food resources, but increased in areas where they had staged historically. An interesting
paradox arises from this situation: when more mussels are cultivated, disturbance for 
waterfowl is greater. The contrast between scaup abundance in areas with high and 
medium aquaculture landings is striking. It could be predicted that medium aquaculture 
areas, with an ample quantity of mussels and moderate levels of disturbance, would 
harbour the most ducks, but this was not the case; the vast majority of ducks were found 
in high aquaculture areas. Food availability in areas with high levels of mussel 
aquaculture could have outweighed the associated disturbances, but it is also possible 
these bays provided the most suitable habitat for scaup (as suggested by their presence 
there prior to establishment of the industry). A more careful look at habitat profitability, 
independent of mussel aquaculture and other disturbances (e.g., boating, hunting, 
fishing), is needed to answer this question. Factors like the presence of refuges in the 
different aquaculture zones could also contribute strongly to the presence of ducks. If, 
for example, there were areas within the high aquaculture zone where scaup could roost 
during the day without being harassed and then feed at night (which they are known to 
do) on the nearby cultivated mussels, use of this habitat could be extremely profitable.

Numbers of Long-Tailed Duck in areas with different levels of aquaculture prior to 1990 
were similar. From 1990 to 2000, the mussel industry expanded six fold. Long-Tailed 
Duck were no longer present in areas with low mussel production, and their numbers 
increased in the two other areas, suggesting that Long-tailed Duck redistributed in areas 
according to levels of mussel aquaculture, with highest numbers found where the most 
mussels were produced. This was not surprising, since Long-tailed Duck were not often 
seen staging in the sheltered bays of P.E.I.; they were usually found further offshore in 
deeper waters (pers. obs). Staging in open water does not restrict the potential for
movement around the island. Consequently, they might be in bays specifically to feed on cultured mussels, and therefore their distribution would be expected to follow development of the industry.

Results from aerial surveys should however be interpreted with caution because of the high variability in duck abundances from year to year. Prior to aquaculture, a count close to the second highest count was observed for Greater Scaup in 1966, and in 1983 for Long-Tailed Duck. It is therefore possible that the high numbers observed in the latter part of the survey could be attributable to this variability. Unfortunately, surveys were less frequent prior to aquaculture, making it difficult to dismiss this possibility.

2.4.3. Relationship between area and duck abundance

The surface area of survey blocks did not differ significantly among levels of aquaculture. Although the analysis did not reveal differences, variability within aquaculture levels was high and therefore reduced the power to detect differences, if any, among mean surface areas. However, waterfowl abundance was not related to survey block surface area during any of the three aquaculture periods. Therefore, previous analyses do not need to be corrected for a potential area effect. Other factors such as cultivated mussels and habitat quality are more likely to have affected waterfowl distribution during the fall staging period.
2.4.4. Issues with interactions between ducks and cultured mussels

Although disturbance of ducks by mussel aquaculture activities does not appear to be a major problem for birds (as suggested by their increasing use of heavily cultured areas), other concerns about the interaction between diving ducks and cultivated mussels exist. Mussels are known to bioaccumulate PCB, and other chlorinated chemicals from pesticides used in agriculture, which can end up in the marine environment (Pruell et al. 1987; Wang et al. 1996). P.E.I.’s bays are surrounded by agriculture fields, and adjacent rivers directly run into the bays. Contamination levels of mussels need to be monitored regularly because of potential for bioamplification in ducks. Exposure to these chlorinated chemicals has been associated with decreased fertility, alteration of immune system and the feminization of male and masculinization of female birds (Colborn et al. 1993; Dewailly et al. 1993; Schimdt 1994).

Waterfowl, in general, show strong site tenacity, leading them to return year after year to the same staging sites (Robertson and Cooke 1999). Although aquaculture started in the 1970’s, it took several years before ducks cued in on this new food resource. First reports of depredation occurred in 1993 (Thompson and Gillis 2001). Future and more intense interactions between diving ducks and cultivated mussels are likely to occur as the mussel industry continues to expand in P.E.I. and elsewhere. Diving duck populations have the potential to increase, as many government agencies have implemented recovery plans to re-establish population to the levels recorded in the 1970s (North American Waterfowl Management Plan 1986). Deterrents (e.g., boat scaring, propane canons) are still not efficient enough to prevent duck predation, and are
often expensive for growers and disruptive for local residents. Many disturbances, both intentional (deterrents) and incidental (aquaculture activities), come with mussel aquaculture. Although waterfowl seem to benefit from the presence of cultivated mussels by an increase in abundance, overall energetic profitability remains questionable. Disturbance can influence a bird’s ability to acquire the necessary nutrient for the different stages of its life cycle (Knapton & al. 2000). Future studies should measure the costs and benefits associated with these interactions.

2.5. Bibliography


Meixner, R. 1986. The predation of mussels by eiders (Somateria mollissima) and its effect on German mussel farming. Ices Council meeting 1986 (collected papers), Ices, Copenhagen (Denmark), 3 pp.


Size selective behaviour of Greater Scaup (*Aythya marila*) feeding on cultivated mussels in Prince Edward Island, Canada.

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**Abstract**

Cultivated blue mussels (*Mytilus edulis*) on long line structures provide an excellent opportunity to study the size-selective behaviour of diving ducks in a natural habitat, while controlling for mussel size availability. Using a commercial and an experimental mussel aquaculture site, I studied the preference of Greater Scaup (*Aythya marila*) for smaller mussels in aquaculture settings. Size-selectivity was tested in relation to two existing hypotheses in an effort to explain this preference for smaller mussels: The shell mass minimisation and the shell crushing minimisation hypotheses. Ducks selected the smallest mussels available. While there was no evidence that they minimised ingested shell, results did support the crushing minimisation hypothesis, in that smaller mussels required less work to break the shells. Results also highlight the importance of multiple hypotheses testing when conducting a prey choice experiment.

Journal to which article will be submitted: **Canadian Journal of Zoologie**

3.1. Introduction

Bivalves, specifically mussels, when available, can be an important part of the Greater Scaup’s (*Aythya marila*) diet (Cottam 1939; Austin *et al.* 1998). Mussels are available across scaups’ range of distribution of both fresh and salt water. A very abundant mussel species found in salt water is the blue mussel (*Mytilus edulis*), which forms patchy beds that vary in depth, density, population size structure (Guillemette *et al.* 1992; Larsen & Guillemette 2000) and quality (Hamilton *et al.* 1999).

Costs associated with foraging on mussels can be divided into two stages: diving and processing. Factors affecting the diving stage include mussel depth, water temperature and current, intake rate, and searching and handling time (Draulans 1982, 1984). Among factors affecting the food processing stage, there is the energy required to crush mussel shells, heat up the food and excrete excess salt intake from mussels because mussels are swallowed whole with cold water (Bustnes and Erikstad 1990; Bustnes 1998; Nehls 2001). Because the energy required by ducks to dive and process mussels is great (De Leeuw and Van Eerden 1992; De Leeuw 1999; Nehls 2001), it is important to select the most profitable prey in order to maximize the net energy intake.
Although diving ducks can eat a wide range of mussel sizes, many are size-selective predators (Guillemette 1994; De Leeuw 1999; Hamilton et al. 1999). Selectivity is defined as consuming co-occurring food sources (or sizes in this case) at different rates relative to their availability (Jacobs 1974). Many hypotheses have been generated to explain this selectivity. Draulans (1982, 1984) linked selection to the risk of taking unprofitable mussels (too large to be swallowed or with low flesh content relative to size). Large mussels also have highly variable flesh content. The increasing risk of taking an unprofitable mussel caused Tufted Ducks (*Aythya fuligula*) to decrease the mean mussel size eaten (risk-averse foraging hypothesis). Nyström and Pehrsson (1988) calculated that the proportion of sea water increased with increasing mussel size and concluded that eiders (*Somateria molissima*) selected small mussels to avoid osmotic stress created by salt water contained in mussels (salt intake minimisation hypothesis). Bustnes and Erikstad (1990) hypothesised that ducks selected small mussels to minimize the proportion of ingested shell, based on the tissue:shell analysis of mussels found in eider gullets (shell mass minimisation hypothesis). De Leeuw and Van Eerden (1992) found that Tufted Ducks ate small mussels because of a more efficient intake rate (intake rate maximization hypothesis). Small mussels, when present in a sufficient number, were obtained by suction feeding, which increased the amount of flesh intake per dive compared to larger mussels. They also discussed selectivity based on the energetic costs of crushing mussels in the gizzard. Costs for crushing are based on shell thickness, thus favouring small mussels (shell crushing minimisation hypothesis). Hamilton *et al.* (1999) found support for both the risk-averse foraging hypothesis and the shell mass minimisation hypothesis for eiders feeding on blue mussels.
Most studies on size-selective behaviour by diving ducks are done either by analysing gullet contents of wild birds or by analysing prey selection by captive ducks in semi-natural conditions. Some bias may occur when analysing gullet contents of wild ducks. Most of the time, it is impossible to know what was selected relative to what was available, because birds were caught in the wild and exact feeding areas prior to sampling are unknown. Selectivity is defined in terms of availability and can be assessed only when availability is measured (Jacobs 1974). Mussel sizes preferred by ducks are known to vary relative to availability (Draulan 1982). Further, processing mussel shells takes twice as much time as ingesting them (Guillemette 1994). Mussels of different sizes might not be processed and excreted by ducks at the same rate. Gullet contents may therefore not be representative of the actual mussel sizes selected during a foraging bout. Bias may also occur when studying selectivity in controlled conditions. The number of birds used in these experiments is often low and the semi-natural conditions are not entirely representative of those found in the wild.

Many studies have looked at interactions between diving ducks and mussel aquaculture (Dunthorn 1971; Heritage 1983; Meixner 1986; Milne and Galbraith 1986; Thompson and Gillis 2001), but none addressed size-selective behaviour of ducks in these settings. Prince Edward Island (P.E.I.), Canada, has a large mussel aquaculture industry that offers an excellent opportunity to study size-selectivity of ducks feeding under natural conditions. There is much anecdotal evidence from P.E.I. that ducks select small mussels, but no formal testing has been done. The arrival of the majority of the ducks (October, November) coincides with seeding (socking) of blue mussel spat on socks suspended in the water column. It is during this period, when the mussels are small, that
they appear to be the most vulnerable and that the majority of losses occur. In recent years, predation by diving ducks cost the P.E.I. industry an estimated $1-2 million annually (Thompson and Gillis 2001) and caused growers to use disruptive scaring tactics (e.g., boat chasing, propane canons) that were only partly effective. A better understanding of this interaction, including the size-selective nature of predation by ducks, is needed in order to find solutions that would allow peaceful coexistence between cultivated mussels and diving ducks.

The goals of this research were to examine the effects that Greater Scaup have on cultivated mussels and to study their size-selective behaviour when feeding on cultivated mussels during the fall and spring staging periods. Mussel size-selectivity in an experimental and commercial mussel site are analysed in relation to the shell-mass minimisation and the shell-crushing minimisation hypotheses. If the dry tissue:shell ratio decreases and crushing resistance increases, as mussels get larger, then ducks should select the smallest prey. Cultivation of mussel on long-line structures provides a unique opportunity to study this behaviour in the natural habitat, while controlling mussel size availability.

3.2. Materials and methods

3.2.1. Commercial culture site

Predation of mussels by Greater Scaup on a commercial culture site in Covehead Bay (adjacent to Brackley Bay) was quantified in November 2001 by underwater sampling
using SCUBA. Covehead Bay is located on the north shore of P.E.I. and has a surface area of approximately 0.38 km$^2$. The damage inflicted on commercial socks was assessed visually using a categorical scale. The scale referred to the proportion of migrated mussels (mussels that were accessible outside the socking material) that were stripped from the socks, and was divided into five intervals (0-20, 21-40, 41-60, 61-80 and 81-100 % damage). The site contained parallel long-lines 12 m apart, maintained at 1.5 m underwater with buoys and cement weights (Figure 3.1). Socks were approximately 2.4 m long and filled (approximately 233 mussels per 30 cm) with different mussel size categories (medium or large) used by the industry. Medium and large mussels ranged between 20-30 mm and 25-35 mm in length, respectively. Socks containing medium or large seeds were positioned alternately on one long-line and spaced by 30 cm. A total of 29 and 25 replicates were sampled for socks containing medium and large mussels, respectively. 180 mussels were measured in each size category to determine mean mussel length.

### 3.2.2. Experimental culture site

An experimental mussel aquaculture site was established in October 2002 in Brackley Bay, P.E.I., Canada. Brackley Bay is located on the north shore of P.E.I., and has a surface area of approximately 0.14 km$^2$. The average depth of the bay is approximately 2 m, but the experimental culture site was set up in an area of the bay 4 m deep. The substrate is composed mainly of silt and mud. The site was set up on long-lines similar to commercial mussel culture sites in adjacent bays. The site
Figure 3.1 Experimental culture site. A. Aerial view of the design. B. Portion of a long-line structure supporting two blocks (caged and uncaged) containing the 6 treatment combinations (3 sizes by 2 densities: T1-T6).
contained three parallel long-lines maintained at 1.5 m underwater with buoys and cement weights. Each line was 60 m long and 12 m apart. Long-lines supported mussel socks filled with different combinations of three mussel size categories (small, medium and large) and two socking densities (minimum and maximum that a sock could contain), for a total of six treatments (Figure 3.1).

Prior to socking, mussel seeds (or wild mussel spat) were collected from spat lines and separated by size in a commercial grader. 50 mussels from each size category were measured to determine mean length. Commercial growers then put mussels into socks (referred to by the industry as Italian type) appropriate for their seed size and soaked them overnight in running water. Total sock length ranged between 125 and 150 cm. Socks were hung on the long-lines at 60 cm intervals the next day. Three socks of every treatment combination were kept and stripped to assess initial mussel densities. A section of 30 cm was chosen randomly (within the bottom or top half) and mussels contained in it counted. Each long-line held 36 socks divided into six unreplicated randomized blocks, where each block contained one replicate of the size by density treatments. Two blocks per line served as predator controls with duck exclusion cages. Exclusion cages were made out of a sturdy black plastic fencing material with 3.8 x 3.8 cm mesh size openings. Cages were built in a cylindrical shape (155 x 145 cm) with closable bottoms.

In order to assess predation by Greater Scaup on the experimental culture site, densities of mussels in the caged (controls) and uncaged treatments were sampled and compared after the fall waterfowl staging period. A 30-cm section of each treatment was chosen
randomly and stripped for counting. Three replicates (or three blocks) for each treatment level were sampled. Densities were assessed initially (October 2002) and in January 2003 for caged and uncaged treatments. After determining that no predation had occurred during the 2002 fall staging period, the experimental culture site was left in place for the 2003 spring staging period. Unfortunately ice destroyed most of the site, leaving only one long-line with three blocks of uncaged treatments and one block of caged treatments by spring. Following two weeks of intense predation in May 2003, mussel densities were assessed in the same way as before (caged and uncaged). Because mussels grew between fall 2002 and spring 2003, 100 mussels from each size category in the caged treatments were measured to determine mean mussel length.

3.2.3. Gullet contents

To estimate the range of mussel sizes eaten by Greater Scaup, seven and four ducks were collected during the fall of 2001 and 2002, respectively. Ducks were shot following hunting regulations and frozen for later analysis. Mussels found in the gizzard and gullet were extracted and lengths measured to the nearest 0.1 mm. The length of broken mussels was estimated using a relationship based on the length of the left internal septum (umbo) and mussel length (Hamilton 1992), calculated for this site using 50 mussels.
3.2.4. Tissue to shell ratio

To test the shell mass minimisation hypothesis, dry tissue to shell weight ratio relative to length was calculated for the different mussel sizes eaten by Greater Scaup. Mussels were sampled where the ducks fed in 2003 (experimental culture site in Brackley Bay) and from another source (St. Peter’s Bay) in 2001. Mussels were frozen and brought back to the laboratory. Samples were then thawed and subsamples representative of the different mussel sizes of each year were chosen randomly for analysis. 148 and 51 mussels were processed in 2001 and 2003, respectively. Mussels were steamed for 5 minutes and dissected to separate the tissue from shell. Tissue and shell were dried at 80°C for 24 hours in a drying oven and weighed to the nearest 0.0001g (Melter AE163 balance). Shells were measured with a digital calliper to the nearest 0.001 mm.

3.2.5. Crushing resistance

To test the shell crushing minimisation hypothesis, costs associated with crushing mussels of different sizes were evaluated. The work needed to crush the left mussel valve was calculated with a material testing machine developed by a faculty member at the Atlantic Veterinary College, University of Prince Edward Island, P.E.I., Canada (W. P. Ireland, unpublished method). The machine had a flat cross head which was actuated on vertical rails by a hydraulic cylinder at a known and controllable speed by a 10 hp hydraulic pump. Mounted on the cross head was a flat platen, which opposed a flat platen, mounted on a 500 kg capacity load cell. A 386 personal computer via a National Instruments A/D converter using LABVIEW software controlled the mechanics. Force
(N), time (sec) and distance (cm) travelled by the cross head to crush mussels were recorded in ASCII files. The work needed to crush mussels represents the surface area under the curve of the force to time relationship. The machine was set so the speed of the cross head averaged 0.015 cm sec⁻¹. 58 mussels from a commercial culture site (Covehead Bay) in the fall 2002 period were processed. The relationship between work needed to crush a mussel shell and length of the mussel measured, was used to create the different tissue:work ratios for mussels that were preyed upon during fall 2001 and spring 2003 (using data on dry tissue mass and length of mussels from section 3.2.4.of this thesis). No crushing measurements were done for mussels under 20 mm. The work needed to crush these mussels was extrapolated from the measured relationship.

3.2.6. Data analysis

All statistical analyses were carried out using SAS Institute software package version 8.2. Significance level (alpha) for main effects and interaction was set to 0.05 and 0.01, respectively. Seed size categories (medium and large) in the commercial culture site were compared using a one-way ANOVA on mussel length. Data failed the normality assumption (Kolmogorov-Smirnov test) and no data transformation (\(\log_{10}\), ln and square root) could resolve the issue. However, the homogeneity of variance assumption was met so analysis was continued with caution for results approaching the significance level. The observed removal of biomass on the socks containing different mussel size classes in the commercial culture site was analysed using a Chi-Square analysis. Nominal scale data were entered in a 2 x 5 contingency table with mussel size category
(medium and large) as the independent variable and percentage of damage (20% intervals) as the dependent variable.

Mussel size categories (small, medium and large) in the experimental culture site (fall 2002 and spring 2003) were compared using a one-way ANOVA. Data were log_{10} transformed to meet assumptions of normality (Kolmogorov-Smirnov test) and homogeneity of variance (Levene’s test). A posteriori comparisons used Tukey’s studentized range tests.

Predation by Greater Scaup in the experimental culture site during fall 2002 was assessed using a three-way unreplicated randomized block analysis of variance on mussel densities for the different size by density treatments. Mussel density was the dependent variable, while mussel size category (small, medium and large), socking density (minimum and maximum) and treatment (Initial, January and January control) were the independent variables. Data were log_{10} transformed to meet the homogeneity of variance assumption.

The size-selective behaviour of Greater Scaup in the experimental culture site during spring 2003 was analysed using an unreplicated randomized block design with two factors. The proportion of dry mussel tissue biomass lost to predation was the dependent variable. Mussel size category (small, medium and large) and socking density (minimum and maximum) were the independent variables. Proportion of dry mussel biomass lost to predation in each sock was estimated by subtracting the dry biomass left in the different treatments from their corresponding controls and dividing it by the latter value. Negative
values were set to zero. Dry mussel biomass is derived from density counts and the relationship between dry mussel weight and length obtained in section 3.2.4. An interaction between mussel size category and socking density was found so the data were recoded as a one-way ANOVA with six treatments. Planned comparisons were carried out between mussel size categories (small vs. medium and medium vs. large) with all densities combined, and among densities for each size category (minimum vs. maximum) for a total of five contrasts. The Dunn-Šidák adjustment to \( \alpha \) for non-orthogonal comparisons was applied (\( \alpha' = 0.01 \)).

The lengths of mussels retrieved in the Greater Scaups’ digestive tracts during fall 2001 and 2002 were compared with a one-way ANOVA.

The relationships of dry tissue:shell mass ratio, shell crushing work and dry tissue mass:shell crushing work ratio on mussel length (independent variable) were analysed using regressions. The tissue:shell ratio on mussel length was a linear relationship, while work and tissue:work ratio on mussel length were quadratic. The intercept for the relationship between work and mussel length was forced to zero. Appropriate regression curves were identified based on residuals and significance of the models.
3.3. Results

3.3.1. Commercial culture site

The two mussel size categories sampled in a commercial culture site (Covehead Bay) differed significantly in mean length (ANOVA; df = 1, 358, F = 291.55, p < 0.0001). The mean length of medium and large mussels ± SD was 24.2 ± 3.9 and 31.2 ± 4.0 mm, respectively.

Commercial socks containing medium mussels were selected over large mussels by Greater Scaup (Table 3.1; 2 x 5 contingency table: df = 4, $\chi^2 = 54$, p < 0.0001). Observed removal on socks containing medium mussels ranged between 61 and 100 %, while the removal of large mussels ranged between 0 and 60%. Data contained many zeros, however, the likelihood of making a type I error is low as results of selectivity are obvious.

<table>
<thead>
<tr>
<th>Size Category</th>
<th>0-20</th>
<th>21-40</th>
<th>41-60</th>
<th>61-80</th>
<th>81-100</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>18</td>
<td>29</td>
</tr>
<tr>
<td>Large</td>
<td>15</td>
<td>9</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td>9</td>
<td>1</td>
<td>11</td>
<td>18</td>
<td>54</td>
</tr>
</tbody>
</table>

Table 3.1 Contingency table (2 x 5) that compares damage caused by Greater Scaup on socks with different mussel size categories (medium and large) in a commercial site (Covehead Bay) during fall 2001. Numbers represent the number of socks in each category.
3.3.2. Experimental culture site

The three mussel size categories used in the experimental culture site differed significantly in mean length (Table 3.2) during October 2002 (ANOVA: df = 2, 297, F = 236.66, p < 0.0001) and May 2003 (ANOVA: df = 2, 297, F = 117.19, p < 0.0001). Tukey’s studentized range *a posteriori* tests revealed that all size categories differed from each other in each sampling period.

**Table 3.2** Mean mussel length (mm) ± SD of three mussel size categories (Small, Medium and Large) used in experimental culture site (Brackley Bay).

<table>
<thead>
<tr>
<th>Period</th>
<th>Mussel size category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small</td>
</tr>
<tr>
<td>Oct 2002</td>
<td>13.0 ± 2.1</td>
</tr>
<tr>
<td>May 2003</td>
<td>16.5 ± 4.9</td>
</tr>
</tbody>
</table>

Greater Scaup did not prey upon mussels in the experimental culture site during the 2002 fall staging period. The three-way ANOVA revealed an interaction between date and socking density (df = 2, 6, F = 2.88, p = 0.0828), so data were recoded as a two-way ANOVA by socking density. Mussel densities in the different size categories remained unchanged between October 2002 (initial) and January 2003 (caged and uncaged) (Tables 3.3 and 3.4).
Table 3.3 Results of a two-way randomized block ANOVA on the mussel density of the different mussel size categories (small, medium & large) in time (initial, January & January control), by socking density (Minimum, Maximum).

<table>
<thead>
<tr>
<th>Density</th>
<th>Source</th>
<th>Error term</th>
<th>DF</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>Size</td>
<td>Size*Block(Date)</td>
<td>2, 12</td>
<td>152.86</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td></td>
<td>Date</td>
<td>Block(Date)</td>
<td>2, 6</td>
<td>0.16</td>
<td>0.8554</td>
</tr>
<tr>
<td></td>
<td>Size*Date</td>
<td>Size*Block(Date)</td>
<td>4, 12</td>
<td>1.36</td>
<td>0.3055</td>
</tr>
<tr>
<td>Maximum</td>
<td>Size</td>
<td>Size*Block(Date)</td>
<td>2, 12</td>
<td>243.72</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td></td>
<td>Date</td>
<td>Block(Date)</td>
<td>2, 6</td>
<td>3.2</td>
<td>0.1135</td>
</tr>
<tr>
<td></td>
<td>Size*Date</td>
<td>Size*Block(Date)</td>
<td>4, 12</td>
<td>1.57</td>
<td>0.244</td>
</tr>
</tbody>
</table>

Table 3.4 Mean mussel density ± SD of the different sock combinations (treatments and controls) in experimental culture site (Brackley Bay) during five sampling periods. Small, medium and large refers to different mussel size categories. Minimum and maximum (Min and Max) refers to socking densities.

<table>
<thead>
<tr>
<th>Sock Density</th>
<th>Mussel density ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Small</td>
<td>656 ± 63.3</td>
</tr>
<tr>
<td>Max Small</td>
<td>1164 ± 26.6</td>
</tr>
<tr>
<td>Min Medium</td>
<td>394.5 ± 3.91</td>
</tr>
<tr>
<td>Max Medium</td>
<td>599.7 ± 18.6</td>
</tr>
<tr>
<td>Min Large</td>
<td>245.8 ± 23.6</td>
</tr>
<tr>
<td>Max Large</td>
<td>356 ± 28.3</td>
</tr>
</tbody>
</table>
Greater Scaup were size-selective predators in their choice of mussels during the 2003 spring migration period, but the effect of mussel size category was influenced by density (Table 3.5). Reanalysis in a one-way ANOVA, showed that Greater Scaup preferred certain treatment combinations to others (Figure 3.2; df = 5, 10, F = 11.31, p = 0.0007). Planned comparisons revealed that ducks showed no preference between small and medium mussels, although the contrast approached significance at the adjusted α (df = 1, F = 9.15, p = 0.0128). Power analysis, however, revealed that there was less than a 40% chance of detecting the observed difference. Ducks preferred medium mussels over large ones (df = 1, 10, F = 18.17, p = 0.0017). Planned comparisons between minimum and maximum densities in each mussel seed category revealed no difference in selection (small: df = 1, 10, F = 0.61, p = 0.4542; medium: df = 1, 10, F = 0.72, p = 0.4147; large: df = 1, 10, F = 1.6, p = 0.2351).

Table 3.5 Results of a three-way ANOVA on the proportion of dry mussel tissue biomass lost to Greater Scaup in May 2003.

<table>
<thead>
<tr>
<th>Source</th>
<th>Error term</th>
<th>DF</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Size*Block</td>
<td>2, 4</td>
<td>11.44</td>
<td>0.0221</td>
</tr>
<tr>
<td>Density</td>
<td>Density*Block</td>
<td>1, 2</td>
<td>0.16</td>
<td>0.1251</td>
</tr>
<tr>
<td>Size*Density</td>
<td>Size<em>Density</em>Block</td>
<td>2, 4</td>
<td>1.36</td>
<td>0.0257</td>
</tr>
</tbody>
</table>
Figure 3.2 Mean proportion of dry mussel biomass lost to Greater Scaup predation (n=3) in the different sock combinations (size category: small medium and large; density: min and max) of experimental culture site. Means with the same letters are not significantly different under $\alpha = 0.01$. 
3.3.3. Gullet contents

Mean mussel sizes in gullets of Greater Scaup during the fall of 2001 and 2002 were similar (t-test: df = 46, T = 1.54, p = 0.1296). Mean mussel lengths (mm) ± SD consumed during fall 2001 and 2002 were 23.3 ± 0.79 and 21.3 ± 0.96, respectively. Maximum mussel length (mm) eaten by Greater Scaup was 30.0 and 28.5 in fall 2001 and 2002, respectively.

3.3.4. Tissue to shell ratio

No relationship was found between the dry tissue:shell weight ratio and mussel length during fall 2001 (Figure 3.3; linear regression: df = 1, 147, F = 0.72, p = 0.3962). The dry tissue:shell weight ratio increased with mussel length during the spring 2003 sampling period (linear regression: df = 1, 50, F = 32.91, p < 0.0001).
Figure 3.3 Regression of dry tissue:shell ratio on length with 95% confidence intervals for cultivated mussels sampled at two different periods.
3.3.5. Crushing resistance

The work needed to crush the left valve of a mussel increased with mussel length in a quadratic relationship (Figure 3.4; quadratic regression: df = 2, 56, \( F = 462.74 \), \( p < 0.0001 \)).

The relationship between the tissue:work ratio and mussel length was also quadratic in both sampling periods (Figure 3.5). The tissue:work ratio during spring 2003 increased with mussel length (Quadratic regression: df = 2, 49, \( F = 14.89 \), \( p < 0.0001 \)), while that in fall 2001 decreased for mussels ranging between 10 to 25 mm in length, and increased for mussels longer than 25 mm (Quadratic regression: df = 2, 146, \( F = 59.25 \), \( p < 0.0001 \)).
Figure 3.4 Regression of work needed to crush left valve of mussel on mussel length with 95% confidence intervals.
Figure 3.5 Regression of dry tissue:work ratio on length confidence intervals for cultivated mussels sampled at two different periods.
3.4. Discussion

3.4.1. Size and density selectivity

The mussel aquaculture setting provided an excellent opportunity to observe the size selective behaviour of ducks when feeding on blue mussels, because proximate mussel availability was controlled. No other mussels were observed in the vicinity of the experimental site (pers. obs.). Selectivity, as defined in terms of availability and prey preference, cannot be assessed if availability is unknown (Jacobs 1974). These settings also provided the opportunity to study bird behaviour in a non-captive state, which more closely resembles what would be observed in the wild.

Data collected from experimental and commercial culture sites clearly demonstrated the size-selective behaviour of Greater Scaup when feeding on blue mussels. During both predation periods, ducks preferred the smallest mussel size category available. In 2001, when only two mussel size categories were present in the commercial site, scaup preyed mainly on the medium size mussels, although they could also eat the large mussels. The mean length of the large mussel size category was 31.2 mm and scaup specimens collected that year revealed that they were capable of eating mussels up to 30.0 mm in length. Although other mussels of unknown sizes were available in the general area (other commercial mussel operations), their influence on the ducks’ selectivity may have been minimal because of the underwater visibility. When diving, all that could be seen was one line with an alternation of medium and large mussel socks. Proximate mussel availability per dive was therefore controlled.
In 2003, Greater Scaup selected the small and medium mussel size categories over the large one, irrespective of density. Although large mussels from 2003 were only 12% longer than those from 2001, they were barely attacked compared to 2001. The presence of a third and smaller size class in 2003 might explain why ducks almost completely avoided the large mussels that year. If ducks had been given sufficient time to consume all the small mussels, they could have switched to larger prey. Tufted Duck in a non-diving situation apparently chose the smallest mussels offered and gradually took the larger mussels, when the smaller ones became scarce (De Leeuw and Van Eerden 1992).

3.4.2. Mussel feeding-related costs

Nehls (2001) concluded that foraging efficiency of mussel-feeding-eiders was very low because 50 to 60% of the assimilated energy was spent during foraging and digestion. Energy costs related to foraging on mussels are high in diving ducks due to thermoregulation costs when diving (De Leeuw 1999) and mechanical costs of diving to overcome buoyancy (De Leeuw and Van Eerden 1992). Woakes and Butler (1983) found that the metabolic rate of Tufted Ducks during submersion was about 3.5 times greater than the resting rate. Decreasing the amount of time spent underwater could therefore reduce foraging costs, increase efficiency and thereby enhance profitability.

Digestion is also a highly energy-consuming process when feeding on mussels. Energy is needed to crush mussel shells, warm the food and excrete excess salt. Almost 20% of the assimilated energy of a mussel is spent crushing the shells (Nehls 2001). In order for ducks to meet their energy requirements when feeding on mussels, they must process a
large quantity of food, because a very small fraction of the total prey weight is organic tissue (ca. 4-6% dry weight) (Thompson 1985). The metabolic rate in eiders can double in response to a single meal of a dozen mussels (Nehls 2001). Foraging costs in diving ducks are high, and any adverse effects on feeding performance will increase daily energy expenses by increasing foraging time (De Leeuw 1999).

3.4.3. Shell mass minimisation hypothesis

The relationships between dry tissue to shell weight ratio and length for cultivated mussels in 2001 and 2003 showed no evidence that eating smaller mussels reduced the proportion of ingested shell. These results contradict those of Bustnes and Erikstad (1990), Bustnes (1998) and Hamilton et al. (1999). Hamilton et al. (1999) found that the consumption of small mussels resulted in more mussel tissue per foraging bout, potentially reducing the amount of time spent feeding, and therefore reducing costs associated with foraging. Results from this study suggest the reverse; dry tissue to shell weight ratios for both sampling periods indicate that when ducks select smaller mussels, they do not reduce the amount of shell ingested. The strong preference observed in Greater Scaup for small mussels suggests that their selectivity is not based on minimising shell mass ingestion, since relatively more shell was ingested per individual mussel during spring 2003. However, explanations based on only one factor do not take into account other important factors that could affect relative profitability of the different mussel sizes. For example, a greater intake rate of small mussels could offset the higher cost of ingesting more shell per tissue, by reducing the time spent foraging and therefore costs associated with feeding, compared to larger mussels.
Previous experiments used subtidal and intertidal mussels rather than the cultivated mussels. Cultivated mussels are grown suspended in the water column and growth rates are higher than wild mussels (Dunthorn 1971; Mallet and Myrand 1995). This higher growth rate apparently increases the dry tissue to shell weight ratio compared with wild mussels (D. Hamilton, unpublished data). Similarly, Bustnes (1998) found that mussels from the subtidal zone had a higher dry tissue to shell weight ratio than intertidal mussels, in which feeding time is periodically stopped by low tide, therefore reducing growth rates. Dry tissue to shell ratios could therefore be site specific. However, Bustnes (1998) also found that eiders were capable of selecting mussels with the least shell content when prey offered were of the same length but from different sources (subtidal and intertidal). If ducks were able to discriminate relative shell mass with such precision, and this was the primary factor influencing their prey selection, one would expect Greater Scaup in this experiment to have chosen the larger mussels during spring 2003, because they yielded relatively less shell per individual mussel.

Dry tissue to shell weight ratio in my experiment did not vary with mussel length in fall 2001, but increased in spring 2003. The difference between periods is probably due to the difference in gonad mass, because fall mussels have just finished spawning, while spring mussels have had time to rebuild gonad tissue mass.
3.4.4. *Shell crushing minimisation hypothesis*

The relationship between work needed to crush shells and mussel length favours the selection of small mussels over larger ones because they require less work. These results are consistent with those of Hamilton *et al.* (1999). Although these results are based on individual mussels, eating small mussels would probably further reduce costs associated with crushing shells because of Newton’s third law of motion: for every action there is an equal and opposite reaction. A duck gizzard filled with only small mussels should require less work than if it was filled only with large mussels, because the total work needed to crush all mussels will not be fully additive. If all mussels were perfectly aligned, the force required to break all shells would be the same as if only one mussel was present. De Leeuw and Van Eerden (1992) concluded that the preference for small mussels was probably a consequence of the habit of crushing the mussels in the gizzard. The energetic cost of crushing is related to shell thickness, thus favouring small mussels.

However, if mussels were considered individually, larger mussels would be favoured over the smaller ones because of their higher tissue to work ratio. Hamilton *et al.* (1999) also found that the larger mussel size classes yielded more energy per unit of work (based only on crushing costs). The main issue here is that mussel profitability relative to its size cannot be assessed on one factor alone. Results of this study highlight the importance of considering more than just energetic profitability per prey item when attempting to determine the optimal prey size for foraging animals (Hamilton *et al.* 1999). Net energy gain per foraging bout should be considered instead, because it would
include important factors like intake rate, which could easily offset profitability of the different mussel sizes by reducing the amount of time spent underwater.

Although the relationship between crushing resistance and mussel length was established during fall 2002 and extrapolated for 2003, the differences among seasons are probably minimal. Shell mass of blue mussels relative to length (and therefore thickness) varied little through the year (Hamilton et al. 1999). Extrapolation of the relationship for mussels in 2001 is, however, more questionable, because mussels used then were from a different source. Experiments on crushing resistance in blue mussels from different growing areas in P.E.I. revealed significant differences (L. A. Mcduffee et al. unpublished data). It is, however, thought that the power relationship between crushing resistance (shell thickness) and mussel length is constant across areas. Blue mussels in P.E.I. from three different sources revealed similar power relationships between shell thickness and mussel length (J.-S. Lauzon-Guay unpublished data).

3.4.5. Other factors in prey selection

The selection of smaller mussels can be explained by other factors as well. For example, De Leeuw and Van Eerden (1992) found that small mussels (< 16mm) were the most profitable due to the handling technique employed by ducks, which increased their intake rate and therefore minimized time spent foraging. Mussels under 16 mm were processed by suction feeding, while larger mussels had to be handled individually. Cultivated mussels used in experimental and commercial sites were mostly over the 16 mm threshold, so handling technique might not have been a factor in prey profitability in
this experiment. However, when mussels were stripped from socks for counting, although no formal measurements were done, it was obvious that the socks containing larger mussels were much harder to process. Large mussels secrete more and stronger byssal threads than smaller mussels (Lee et al. 1990). Ducks could have therefore removed smaller mussels more easily and filled up on them more quickly than they would have on larger ones, thus reducing the amount of time spent underwater. The food intake rate of Tufted Ducks (Aythya fuligula) decreased with the strength of byssal thread attachment of mussels (De Leeuw 1999). On the other hand, Draulans (1982) and Hamilton et al. (1999) concluded that the effect of byssal attachment relative to mussel size on prey profitability was minimal. However, profitability in these cases was considered on individual mussels and no formal testing on the effect of byssal strength attachment was done. Future experiments should try to address the effect of byssal attachment on mussel profitability per foraging bout to determine if it is biologically significant.

Eating smaller mussels could reduce the time required to crush mussel shells, since smaller mussels require less work to break their shells. If mussels can be digested more rapidly, then ducks may be able to come closer to maximizing their ingestion rate, and could therefore fulfill daily energy requirements in less time, thus enhancing profitability. Guillemette (1994) and De Leeuw (1999) found evidence that eiders were limited by digestive constraints when feeding on mussels. Guillemette (1994) discovered that eiders ingested blue mussels twice as fast as they were able to digest them. If the digestion rate is lower than the ingestion rate, ingestion rate is unlikely to be maximized (Verlinden and Wiley 1989).
Eating smaller mussels could also reduce the energy costs associated with excreting excess salt. Nyström and Pehrsson (1987) showed that the proportion of seawater increased with increasing mussel sizes. Eating smaller mussels would therefore reduce the net energy costs to ducks.

3.4.5 Industry related issues

Mussel growers should avoid setting up commercial mussel operations in areas where diving ducks are known to stage in high numbers during the fall, because most mussel seed sizes used are vulnerable when put in the water for their growing phase. Greater Scaup in the experimental culture site ate all of the available small mussel seeds and most of the medium-sized ones. Based on the gullet samples and the observed damage on a commercial site, scaup can also eat most of the larger mussel seeds that are put in the water each fall, although they are clearly not the preferred ones. If a mussel culture lease already exists in an area where ducks are present, growers should try to acquire and use the larger mussel seeds in order to reduce losses to diving ducks. Changing mussel socking density will, however, not reduce predation, as seen from the results in experimental culture site. Growers should also consider where they put their mussel socks with different seed sizes in their culture lease. Putting the smaller mussels away from ducks and in areas where disturbances are high (e.g., boat traffic, close to roads, hunting) could also help to reduce losses without inflicting additional disturbance, which can be detrimental to birds (Knapton et al. 2000).
3.4.6. Conclusion

The only way for ducks to minimise the time spent diving is to increase their mussel intake rate. Selecting smaller mussels could increase the intake rate because of easier handling and weaker byssal attachment. Digestion costs could also be decreased by selecting small mussels. Smaller mussels would be easier and quicker to crush, while reducing the amount of excess salt ingested, which requires energy to excrete.

There are many possible explanations for why ducks select relatively small mussels. Future studies should try to incorporate multiple hypotheses testing to explore the relative importance of each. Energetic gain per individual mussel should be replaced by energetic gain per dive in order to account for intake rate, which can easily offset profitability of the different size mussels. The use of underwater video systems could facilitate such studies, and aquaculture sites, which allow control over the availability of mussels of the different sizes, could provide excellent settings for these experiments. Attention should also be focused on quantifying relative costs in digestion (time, crushing and salt excretion) when consuming mussels of different sizes by measuring oxygen consumption of captive birds in respiratory chambers.

Mussel growers need to develop protective measures for their crop, because current scaring techniques are only partially effective and can be disturbing for staging waterfowl. The use of different seed sizes to mitigate predation by diving ducks will not be sufficient because they can eat most of the seed sizes that are put out during the fall. Because mussels do not grow very much during winter, they remain vulnerable the
following spring. Although ducks are not as numerous and do not stay as long in spring as during the fall, there have been reports of predation during the spring staging period in P.E.I. Careful monitoring should be carried out to assess the extent of damage cause by ducks during spring and to compare behaviour and numbers of ducks during the fall and spring staging periods.

3.5. Bibliography


Meixner, R. 1986. The predation of mussels by eiders (Somateria mollissima) and its effect on German mussel farming. Ices Council meeting 1986 (collected papers), Ices, Copenhagen (Denmark), 3 pp.


Protective socking material for cultivated mussels: a potential non-disruptive deterrent to reduce losses to diving ducks.

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Abstract

Predation of cultivated mussels by diving ducks can threaten the viability of mussel farms. Conventional scaring tactics have proven to be ineffective at deterring ducks from feeding on cultivated mussels because of rapid habituation and 24-hour feeding cycles in some waterfowl species. I tested a socking material containing a protective biodegradable layer against predation by diving ducks on an experimental blue mussel (Mytilus edulis) aquaculture site in P.E.I., Canada. Results showed that the protective socking has the potential to reduce losses to ducks, but did not perform well for all mussel seed sizes used by the industry. The protective layer also did not biodegrade fast enough, trapping a portion of mussels inside the sock, potentially affecting the growth rate of these mussels. Improvements are needed to make this solution effective for all mussel sizes used by the industry and to make its production more cost effective.

Journal to which article will be submitted: Journal of Shellfish Aquaculture
4. Protective socking material for cultivated mussels: a potential non-disruptive deterrent to reduce losses to diving ducks.

4.1. Introduction

Mussel aquaculture has become in important industry in many parts of the world. Like agriculture, aquaculture concentrates large quantities of high quality food, providing an attractive food source for unwanted wild animals (Van Vuren and Smallwood, 1996). Mussel aquaculture in Prince Edward Island, Canada, started in the 1970’s. The industry expanded six fold during the 1990’s, reaching an annual production of 17,000,000 kg. It was during this time that interactions with diving ducks became problematic, threatening the viability of certain mussel operations (Thompson and Gillis, 2001). Predation, mainly by Greater Scaup (*Aythya marila*) and Long-Tailed Duck (*Clangula hyemalis*), generally takes place during the fall migration period, when ducks are most abundant in the area. This timing coincides with collection and socking of mussel spat, which is very vulnerable to predation because of its small size. Cultivated mussels are also present in high density, year after year at the same place, and have thinner shells than wild mussels (Dunthorm, 1971), thus enhancing prey profitability.

In response to increasing losses, growers started using different deterring techniques to reduce predation pressure by diving ducks on mussel farms. Visual deterrents such as scarecrows usually resulted in rapid habituation by the birds (Burnett *et al*. 1994; Ross *et
Acoustic deterrents such as propane canons achieved similar results, as well as disturbing surrounding residents. Ross et al. (2001) conducted promising trials using an underwater playback system (UPS) on mussel farms in Scotland, but this deterrent, even when supplemented with boat chasing, had an effective range of less than 100 m (Thompson and Gillis, 2001). Currently, the best known scaring tactic used in P.E.I. is chasing ducks in boats all day and occasionally reinforcing the threat with starter pistols. However, this is not an entirely satisfactory solution to the problem due to costs associated with the method, and the fact that boat chasing can also be very disruptive for other wildlife using these habitats. Some waterfowl species (*Aythya spp.*) also feed at night (McNeil et al. 1992), rendering daytime boat chasing ineffective. There have been reports of serious damage by scaup occurring over a few nights in P.E.I. (R. Murphy, pers. com.). Other waterfowl species that feed extensively on mussels are also capable of adapting their foraging pattern in order to meet daily energy requirements. Systad and Bustness (2001) observed wintering Steller’s Eiders (*Polysticta stelleri*) in northern Norway feeding at night. Ross (2000) studied the use of a powerful laser light, a deterrent that can also be used at night, and obtained promising results. However the laser does not work in bright light conditions and has an effective range of about 100 m. There is also evidence that some birds do not scare in the presence of the laser (McKay et al. 1999).

Anthropogenic disturbances can compromise the ability of ducks to acquire the body fat necessary for migration and overwintering survival (Haramis et al. 1986; Kahl, 1991).
This, combined with the ineffectiveness of existing techniques, suggests that new deterents that are less disruptive and can offer 24-hour protection are needed to foster peaceful co-existence between migrating waterfowl and mussel growers.

A potential solution proposed by the industry is a protective socking material. This material consists of the standard polypropylene sleeve with a biodegradable protective layer stitched around it. When mussels are put into socks and hung in the water, they start migrating toward the outside of the sock in order to filter feed properly, making them vulnerable to predation by diving ducks. The purpose of the second layer, with its smaller mesh openings, is to prevent mussels from migrating outside the sock, keeping them between the layers until the predation threat is over. The protective layer then breaks down without hindering mussel growth.

The purpose of this study was to test the potential of the protective socking material as an effective deterrent to prevent duck predation on cultivated mussels in P.E.I. Vulnerability of the mussels in the regular and protective material, effectiveness of the protective material against predation, and biodegradation of the protective layer were tested in two experimental culture sites.

As the mussel industry expands, so will the conflicts with diving ducks. Efficient non-disruptive solutions are therefore needed because diving ducks and mussel aquaculture share common habitats. Results from this study could be applicable in other part of the world where interaction between mussel aquaculture and diving ducks exist: British Columbia, Eastern Canada, United States, Scotland, Germany, Holland, Norway, etc.
4.2. Materials and methods

4.2.1. Experimental culture site

Two experimental mussel aquaculture sites were established in October 2002, in Brackley Bay and New London Bay, Prince Edward Island (P.E.I.), Canada. Brackley Bay is located on the north shore of P.E.I., and has a surface area of approximately 0.14 km². The average depth of the bay is approximately 2 m, but the experimental culture site was set up in the area of maximum depth (4 m). The substrate is composed mainly of silt and mud. New London is also located on the north shore and has a surface area of approximately 16 km². Average depth of the bay is approximately 4 m and the site was set up in an area 4.5 m deep. The substrate is also composed mainly of silt and mud, but contrary to Brackley Bay, New London has a wide opening to the ocean, which increases water current and renewal.

The sites were set up on long-line structures similar to commercial mussel culture sites in that area. The sites contained three parallel long-lines maintained at 1.5 m underwater with buoys and cement weights. Lines were 60 m long and 12 m apart. Long-lines supported mussel socks filled with different combinations of three mussel size categories.
(small, medium and large) and two socking materials (Figure 4.1; regular and protective), for a total of six treatments (Figure 4.2).

The regular socking materials used were the GDI-4S, GDI-5M, GDI-7L, for small medium and large mussels respectively. GDI socks are referred to as Irish socks and are made of interwoven, flattened polypropylene strands. GDI socks are produced and distributed by Go-Deep International, Fredericton, New Brunswick (Canada). The protective socking material used comprised regular mussel socks with a biodegradable, loop-knitted sleeve in a 50:50 cotton: polyester blend sewn over the polypropylene strands, giving it a protective layer.

Prior to socking, mussel seeds were collected from spat lines and separated by size in a commercial grader. 50 mussels from each size category in Brackley Bay, and 100 in New London Bay, were measured to determine mean length. Commercial growers then put mussels into socks appropriate for their seed size and soaked them overnight in running water. Total sock length ranged between 125 and 150 cm. Socks were hung on the long-lines at 60 cm intervals the next day. Three socks of every treatment combination from each site were kept and stripped to assess initial mussel densities. A section of 30 cm was randomly chosen and mussels contained in it counted. Each long-line in Brackley Bay held 36 socks divided into six unreplicated randomized blocks, where each block contained one replicate of each treatment. Long-lines in New London Bay held 54 socks (9 blocks) set up in a similar way. Two and three blocks per line
Figure 4.1 Examples of freshly socked mussels in the different socking materials used in experimental culture sites. A. Regular material (GDI-7L). B. Protective material (GDI-7L + GDI 50:50 cotton: polyester blend.)
Figure 4.2 Experimental culture site. A. Aerial view of the design. B. Portion of a long-line structure supporting two blocks (caged and uncaged) containing the 6 treatment combinations (3 sizes by 2 densities:T1-T6).
served as predator controls with duck exclusion cages in Brackley Bay and New London Bay, respectively. Exclusion cages were made of a sturdy black plastic fencing material with 3.8 x 3.8 cm mesh size openings. Cages were built in a cylindrical shape (155 x 145 cm) with closable bottoms.

4.2.2. Mussels lost to predation by diving ducks

In order to assess predation by Greater Scaup on experimental culture sites, densities of mussels in caged and uncaged treatments were sampled and compared after the fall waterfowl staging period in both bays. A 30-cm section of each sock treatment was randomly chosen and stripped for counting. Three replicates for each treatment (size by material type) were sampled. Densities were assessed initially (October 2002) and in January 2003 for caged and uncaged treatments. After determining that no predation had occurred during the 2002 fall staging period, the experimental culture sites were left in place for the 2003 spring staging period. Unfortunately, ice destroyed most of the Brackley Bay site, leaving only one long-line with three blocks of uncaged socks and one block of caged socks by spring. Following two weeks of intense predation in May 2003 (in Brackley Bay only), mussel densities were assessed in the same way as before (cage and uncaged), in both sites. Because mussels grew between fall 2002 and spring 2003, 100 mussels from each size category (caged treatments) in each site were measured to determine mean mussel length.
4.2.3. Migration of mussels through different socking materials during fall 2003

Cultured mussel vulnerability to duck predation, in regular and protective socking materials, was assessed by quantifying the migration of mussels through the socks. Mussel migration was estimated in both bays on one block of caged and uncaged treatments per line, following a repeated measures design where a mussel sock is the replicate. A random section of 33 cm in the bottom and top half of each sock was sampled visually using SCUBA. All mussels that had at least 50% of their volume outside the sock were counted in a 180° field of view. Both halves of each sock (top and bottom) were average to estimate mussel migration per sock. The blocks from Brackley Bay were sampled four times, while those from New London Bay were sampled three times.

4.2.4. Biodegradation of protective layer

Biodegradation of the cotton (50%) – polyester (50%) layer from the protective socking materials was estimated by measuring its tensile strength. Resistance was measured in socks from experimental culture sites containing different mussel seed sizes, and at various times. For this a third experimental site, identical to New London Bay (section 4.2.1), was added. The site was established in St. Peter’s Bay on the North shore of P.E.I. The bay has a surface area of approximately 14 km², with a muddy substrate and an average depth of about 4 m. New socks (n= 3) for each mussel size were sampled each time from randomly chosen blocks without exclusion cages. Socks from New
London and St. Peter’s Bay were sampled three times, and those from Brackley Bay twice. The initial strength of the protective material on the different socks (for each mussel size) was calculated using three replicates of each sock that never went into the water. These results were used as initial strength for all three sites.

Resistance of the protective layer in a sock was estimated using the average strength of 20 individual threads from that sock. The number of threads to pull from a sock was determined by running average. A mean was calculated after five tensile measurements and recalculated with each new measurement. All means were plotted and the number of threads to pull was determined when means seemed to level off (new measurements no longer affected the mean). The strength of a thread was measured using a homemade tensiometer (Figure 4.3). To measure the strength of a thread, these steps were carefully followed: 1) attach one thread with a simple knot to the fishing line loop, 2) bring measuring gauge to calibrating point, 3) pull thread by one end slowly and constantly until it breaks, 4) measure distance on syringe with a calliper (±0.05 mm), and 5) convert distance into a weight resistance (g). Threads that broke inside the knot loop were discarded. The relationship between spring elongation and weight resistance was established using a Newtonmeter (maximum weight: 1000g). Five measurements of the spring length were conducted at each of the four weight resistances (200, 300, 400, 500 g).
Figure 4.3 Homemade tensiometer with its various parts

A. Fibre glass mounting plate
B. Pin to keep spring in its position
C. 3 cm Trakar spring (TE57)
D. Syringe fixed on mounting plate
E. Fishing line
F. Loop in fishing line to attach thread
G. Calibrate point where spring tension = 0 g
H. Cardboard piece for measuring (gauge)
I. Anti-reverse foam piece to measure maximum distance until thread breaks
J. Knot in fishing line for a one-way movement of gauge
K. Thread of protective material attached with a simple knot.
4.2.5. Data analysis

All statistical analyses were carried out using SAS Institute software package version 8.2. Significance level (alpha) for main effects and interaction was set to 0.05 and 0.01, respectively. Mussel size categories (small, medium and large) in experimental culture sites were compared using a one-way ANOVA. Data were log\(_{10}\) transformed to meet assumptions of normality (Kolmogorov-Smirnov test) and homogeneity of variance (Levene’s test). A posteriori comparisons were done using Tukey’s studentized range tests.

Predation by Greater Scaup in the experimental culture sites during fall 2002 was assessed using a three-way randomized block design on mussel densities for the different socking treatments. Mussel density was the dependent variable, while mussel size category (small, medium and large), socking material (regular and protective) and sample (Initial, January and January control) were the independent variables. Data were log\(_{10}\) transformed to meet the homogeneity of variance assumption. Data from New London Bay showed some violation of statistical assumptions. Homogeneity of variance was not met for all levels of factors. A graphical representation of the log\(_{10}\) residuals plotted by size showed that there was more variance associated with the large mussels, but also that the residuals were not unacceptable. ANOVA is robust in these situations (Winer et al. 1991) and no results were close to the p= 0.05 threshold, making their interpretation reliable.
The migration of the different mussel seed categories through the socking materials over time was analysed using a repeated measures ANOVA. The number of migrated mussels was the dependant variable, while mussel seed size (small, medium large), socking material (regular, protective), block and exclusion cages (present, not present) nested in block were the independent variables. The two sites were analysed separately.

The effectiveness of the protective socking material against predation by Greater Scaup in Brackley Bay’s experimental culture site during spring 2003 was analysed using an unreplicated randomized block ANOVA with two factors. The proportion of dry mussel tissue biomass lost to predation was the dependent variable. Mussel size category (small, medium and large) and socking material (regular and protective) were the independent variables. The proportion of dry mussel biomass lost to predation in each sock was estimated by subtracting the dry biomass left in the different treatments from their corresponding controls and dividing it by the later value. One proportion gave a negative value and was set to zero. Dry mussel biomass is derived from density counts and the existing relationship between dry mussel weight and length obtained in Chapter 3, section 3.2.4.

Calibration of the homemade tensiometer was done using simple linear regression where spring elongation was the dependent variable and weight resistance was the independent variable. The intercept was set to zero. Biodegradation of the protective layer in protective socking material in time was analysed in two parts. First, data from all three bays from October 2002 to May 2003 were analysed using a three-way unreplicated randomized block design were tensile strength was the dependent variable, and site,
mussel seed size and date were the independent variables. The second part encompassed data from October 2002 to August 2003 for New London Bay and St. Peter’s Bay only, and was analyzed the same way.

4.3. Results

4.3.1. Mussel size distribution

The three mussel size categories used in Brackley Bay’s experimental culture site differed significantly in mean length (Table 4.1) during October 2002 (ANOVA: df =2, 148, F = 236.66, p < 0.0001) and May 2003 (ANOVA: df = 2, 297, F = 117.19, p < 0.0001). A posteriori tests revealed that all categories were different from one another in each sampling period. The three mussel size categories used in New London Bay also differed significantly in mean length (Table 4.1) during October 2002 (ANOVA: df =2, 297, F = 278.2, p < 0.0001) and May 2003 (ANOVA: df = 2, 297, F = 133.98, p < 0.0001). A posteriori tests revealed that all categories were different from one another in each sampling period.
Table 4.1 Mean mussel length (mm) ± SD of three mussel size categories (Small, Medium and Large) used in experimental culture sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Period</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brackley</td>
<td>Oct 02</td>
<td>13.0 ± 2.1</td>
<td>19.0 ± 3.5</td>
<td>26.7 ± 4.0</td>
</tr>
<tr>
<td></td>
<td>May 03</td>
<td>16.5 ± 4.9</td>
<td>25.3 ± 7.3</td>
<td>35.6 ± 6.6</td>
</tr>
<tr>
<td>New London</td>
<td>Oct 02</td>
<td>14.6 ± 3.2</td>
<td>21.6 ± 3.4</td>
<td>26.3 ± 4.0</td>
</tr>
<tr>
<td></td>
<td>May 03</td>
<td>19.3 ± 5.3</td>
<td>26.5 ± 5.8</td>
<td>31.5 ± 4.8</td>
</tr>
</tbody>
</table>

4.3.2. Mussels lost to predation by diving ducks during fall 2002

The mussel densities of the different sock combinations in Brackley Bay remained unchanged from October 2002 to January 2003 in both caged and uncaged blocks (Table 4.2). Statistical analysis revealed no difference among the three samples (October, January and January control) (df= 2, 6, \( F = 0.17 \), \( p = 0.8498 \)). Densities, however, differed among sizes (df= 2, 12, \( F = 85.87 \), \( p < 0.0001 \)), being greater in socks filled with small mussels than the rest. Densities also differed between sock types (df=1, 6 \( F = 20.43 \), \( p = 0.004 \)). The protective material contained more mussels than the regular material, all sizes pooled (Table 4.2).

Analysis of the mussel densities in New London Bay revealed an interaction between size and date (df= 4, 10, \( F = 13.12 \), \( p = 0.0005 \)) so the analysis was recoded and run by size. Densities of socks filled with small mussels remained the same in all three samples.
(df= 2, 5, F= 0.72, p= 0.5328), but differed among sock types, with higher densities in
the protective socks (Table 4.2; df=1, 5, F= 10.55, p= 0.0228). Densities of socks
containing medium mussels also remained unchanged in all three samples (df= 2, 5, F=
0.73, p= 0.5270), and were different among sock type with higher densities in the
protective socks (Table 4.2; df= 1, 10, F= 12.34, p= 0.0170). The densities of socks
filled with large mussels varied among the three samples, with lower initial densities
(Table 4.2; df= 2, 5, F= 45.67, p= 0.0006), and between sock type, again with higher
densities in the protective socks (Table 4.2; df= 1, 5, F= 9.11, p= 0.0295).
Table 4.2 Mean mussel density ± SD of the different sock combinations (treatments and controls) in two experimental culture sites during five sampling periods.

<table>
<thead>
<tr>
<th>Sock Size category (Type)</th>
<th>Mussel density ± SD</th>
<th>Brackley Bay</th>
<th>Oct 2002 (Initial)</th>
<th>Jan 2003 (Control)</th>
<th>May 2003</th>
<th>May 2003 (Control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>small regular</td>
<td>529 ± 78.52</td>
<td>460.4 ± 177.91</td>
<td>532.03 ± 80.2</td>
<td>152.33 ± 15.6</td>
<td>628</td>
<td></td>
</tr>
<tr>
<td>medium regular</td>
<td>378 ± 18.19</td>
<td>292.99 ± 35.32</td>
<td>259.48 ± 29.3</td>
<td>67.67 ± 29.74</td>
<td>292</td>
<td></td>
</tr>
<tr>
<td>large regular</td>
<td>341 ± 5.39</td>
<td>322.9 ± 35.49</td>
<td>358.73 ± 96.62</td>
<td>303 ± 38.63</td>
<td>237</td>
<td></td>
</tr>
<tr>
<td>small protected</td>
<td>645 ± 87.32</td>
<td>769.09 ± 123.7</td>
<td>669.48 ± 152.5</td>
<td>135.33 ± 83.2</td>
<td>1064</td>
<td></td>
</tr>
<tr>
<td>medium protected</td>
<td>352.5 ± 8.85</td>
<td>403.58 ± 51.56</td>
<td>463.89 ± 111.2</td>
<td>228.3 ± 35.02</td>
<td>428</td>
<td></td>
</tr>
<tr>
<td>large protected</td>
<td>314.33 ± 8.01</td>
<td>420.38 ± 76.88</td>
<td>419.72 ± 19.93</td>
<td>402.7 ± 25.43</td>
<td>489</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>New London Bay</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>small regular</td>
<td>291.67 ± 23</td>
<td>273.64 ± 5.39</td>
<td>313.21 ± 24.65</td>
<td>294 ± 32.04</td>
<td>290.5 ± 31.82</td>
<td></td>
</tr>
<tr>
<td>medium regular</td>
<td>291.17 ± 2.91</td>
<td>287.35 ± 27.86</td>
<td>261.57 ± 55.77</td>
<td>243.83 ± 29.3</td>
<td>226.5 ± 44.6</td>
<td></td>
</tr>
<tr>
<td>large regular</td>
<td>309.67 ± 7.67</td>
<td>413.88 ± 95.13</td>
<td>382.1 ± 34.61</td>
<td>350.3 ± 41.99</td>
<td>313 ± 45.25</td>
<td></td>
</tr>
<tr>
<td>small protected</td>
<td>381.67 ± 7.26</td>
<td>347.21 ± 45.63</td>
<td>334.84 ± 61.46</td>
<td>372.5 ± 33.92</td>
<td>360 ± 26.87</td>
<td></td>
</tr>
<tr>
<td>medium protected</td>
<td>329.3 ± 14.29</td>
<td>361.72 ± 0.52</td>
<td>340.15 ± 28.82</td>
<td>338.33 ± 36.3</td>
<td>379.5 ± 9.19</td>
<td></td>
</tr>
<tr>
<td>large protected</td>
<td>321.83 ± 9.22</td>
<td>555.1 ± 68.74</td>
<td>540.98 ± 85.02</td>
<td>410 ± 69.25</td>
<td>388 ± 15.56</td>
<td></td>
</tr>
</tbody>
</table>
4.3.3. *Migration of mussels through the different socking materials*

during fall 2003

The repeated measures analysis of mussel migration through socking material in Brackley Bay (Table 4.3) revealed multiple interactions: mussel size * date (Pillai’s Trace: df= 6, 14, F= 7.25, p= 0.0011), mussel size * sock type * date (Pillai’s Trace: df= 6, 14, F= 2.33, p= 0.0902) and mussel size * sock type (between subject effect: df= 2, 8, F= 122.8, p< 0.0001), so the analysis was recoded and run by size.

Migration rate of small mussels (comparison of slopes) was faster in the protective socking material, and more mussels migrated out than in the regular material (Figure 4.4 and Table 4.3; Small). The presence of exclusion cages did not affect the rate of migration for small mussels or the number of migrated mussels in both sock types (Figure 4.4, Table 4.3; Small). The different sock types did not influence the migration rate of medium mussels, however, more mussels migrated out of the regular socking material (Figure 4.4 and Table 4.3; Medium). The presence of exclusion cages did not affect migration rate of medium mussels or the amount of migrated mussels (Figure 4.4 and Table 4.3; Medium). The migration rate of large mussels was not affected by the different sock types, however, more mussels migrated out of the regular socking material (Figure 4.4 and Table 4.3; Large). The presence of exclusion cages did not affect migration of large mussels over time or the amount of migrated mussels (Figure 4.4 and Table 4.3; Large).
Figure 4.4 Mean mussel migration ± SD through different socking materials for three mussel seed categories, from 2 November 2002 to 27 January 2003 in Brackley Bay.
Mean mussel migration per section of 33 cm.

Small
- Protected caged
- Protected uncaged
- Regular caged
- Regular uncaged

Medium

Large

Date
04/11  02/12  30/12  27/01
Table 4.3. Results of a repeated measures analysis for the migration of mussels through different socking materials (caged and uncaged) from 2 November 2002 to 27 January 2003 in Brackley Bay.

**Brackley Bay**

<table>
<thead>
<tr>
<th>Size</th>
<th>Effect</th>
<th>DF</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>Among-subject*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Date*cage</td>
<td>3,2</td>
<td>0.77</td>
<td>0.6066</td>
</tr>
<tr>
<td></td>
<td>Date*sock type</td>
<td>3,2</td>
<td>15.88</td>
<td>0.0598</td>
</tr>
<tr>
<td></td>
<td>Date<em>cage</em>sock type</td>
<td>3,2</td>
<td>0.23</td>
<td>0.8710</td>
</tr>
<tr>
<td></td>
<td>Within-subject</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cage</td>
<td>1,4</td>
<td>0.00</td>
<td>0.9980</td>
</tr>
<tr>
<td></td>
<td>Sock type</td>
<td>1,4</td>
<td>108.60</td>
<td>0.0005</td>
</tr>
<tr>
<td></td>
<td>Cage*sock type</td>
<td>1,4</td>
<td>0.34</td>
<td>0.5896</td>
</tr>
<tr>
<td>Medium</td>
<td>Among-subject *</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Date*cage</td>
<td>3,2</td>
<td>1.47</td>
<td>0.4301</td>
</tr>
<tr>
<td></td>
<td>Date*sock type</td>
<td>3,2</td>
<td>0.66</td>
<td>0.6490</td>
</tr>
<tr>
<td></td>
<td>Date<em>cage</em>sock type</td>
<td>3,2</td>
<td>7.66</td>
<td>0.1176</td>
</tr>
<tr>
<td></td>
<td>Within-subject</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cage</td>
<td>1,4</td>
<td>1.32</td>
<td>0.3148</td>
</tr>
<tr>
<td></td>
<td>Sock type</td>
<td>1,4</td>
<td>17.44</td>
<td>0.0140</td>
</tr>
<tr>
<td></td>
<td>Cage*sock type</td>
<td>1,4</td>
<td>0.07</td>
<td>0.8013</td>
</tr>
<tr>
<td>Large</td>
<td>Among-subject *</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Date*cage</td>
<td>3,2</td>
<td>7.49</td>
<td>0.1201</td>
</tr>
<tr>
<td></td>
<td>Date*sock type</td>
<td>3,2</td>
<td>4.67</td>
<td>0.1814</td>
</tr>
<tr>
<td></td>
<td>Date<em>cage</em>sock type</td>
<td>3,2</td>
<td>0.95</td>
<td>0.5503</td>
</tr>
<tr>
<td></td>
<td>Within-subject</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cage</td>
<td>1,4</td>
<td>0.42</td>
<td>0.5545</td>
</tr>
<tr>
<td></td>
<td>Sock type</td>
<td>1,4</td>
<td>267.50</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Cage*sock type</td>
<td>1,4</td>
<td>0.01</td>
<td>0.9172</td>
</tr>
</tbody>
</table>

* Pillai’s trace F-Value was used for the among subject effect.
Analysis of mussel migration in New London Bay (Figure 4.5) also yielded a significant interaction between mussel size and sock type (between subject effect: df= 2, 6,  F= 13.72,  p= 0.0058), so the repeated measures analysis was run by size. Socking material did not influence the migration rate of small mussels or the amount of migrated mussels (Figure 4.5 and Table 4.4; Small). The presence of exclusion cages also did not affect migration rate of small mussels or the amount of migrated mussels (Figure 4.5 and Table 4.4; Small). Migration rate of medium mussels and numbers of migrated mussels were not affected by sock type (Figure 4.5 and Table 4.4; Medium). Migration rate of medium mussels was also not influenced by the presence of exclusion cages, but more mussels migrated out of the socks with exclusion cages (Figure 4.5 and Table 4.4; Medium). Contrasts (Treatments vs. controls) between successive dates however, revealed no differences (Nov 15th vs. Nov 27th: df= 1, 3,  F= 0.14,  p=0.7291; Nov 27th vs. Jan 29th: df= 1, 3,  F= 0.46,  p= 0.5680). Migration of large mussels in time was not affected by sock type but more mussels migrated out of the regular material (Figure 4.5 and Table 4.4; Large). The presence of exclusion cages did not affect migration rate of large mussels or the amount of migrated mussels (Figure 4.5 and Table 4.4; Large).
Figure 4.5 Mean mussel migration ± SD through different socking materials for three mussel seed categories, from 15 November 2002 to 29 January 2003 in New London Bay.
Mean mussel migration per section of 33 cm.

**Small**
- Protected caged
- Protected uncaged
- Regular caged
- Regular uncaged

**Medium**

**Large**

Date
10/11  08/12  05/01  02/02
Table 4.4. Results of a repeated measure analysis for the migration of mussels through different socking materials (caged and uncaged) from 15 November 2002 to 29 January 2003 in New London Bay.

<table>
<thead>
<tr>
<th>Size</th>
<th>Effect</th>
<th>DF</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Among-subject*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td>Date*cage</td>
<td>2,2</td>
<td>0.42</td>
<td>0.7222</td>
</tr>
<tr>
<td></td>
<td>Date*sock type</td>
<td>2,2</td>
<td>3.10</td>
<td>0.2437</td>
</tr>
<tr>
<td></td>
<td>Date<em>cage</em>sock type</td>
<td>2,2</td>
<td>2.23</td>
<td>0.3097</td>
</tr>
<tr>
<td>Medium</td>
<td>Date*cage</td>
<td>2,2</td>
<td>0.15</td>
<td>0.8678</td>
</tr>
<tr>
<td></td>
<td>Date*sock type</td>
<td>2,2</td>
<td>0.95</td>
<td>0.5123</td>
</tr>
<tr>
<td></td>
<td>Date<em>cage</em>sock type</td>
<td>2,2</td>
<td>0.66</td>
<td>0.6035</td>
</tr>
<tr>
<td>Large</td>
<td>Date*cage</td>
<td>2,2</td>
<td>1.01</td>
<td>0.4983</td>
</tr>
<tr>
<td></td>
<td>Date*sock type</td>
<td>2,2</td>
<td>0.39</td>
<td>0.7189</td>
</tr>
<tr>
<td></td>
<td>Date<em>cage</em>sock type</td>
<td>2,2</td>
<td>0.01</td>
<td>0.9872</td>
</tr>
<tr>
<td></td>
<td>Cage</td>
<td>1,3</td>
<td>19.05</td>
<td>0.0222</td>
</tr>
<tr>
<td></td>
<td>Sock type</td>
<td>1,3</td>
<td>3.70</td>
<td>0.1502</td>
</tr>
<tr>
<td></td>
<td>Cage*sock type</td>
<td>1,3</td>
<td>1.02</td>
<td>0.3867</td>
</tr>
</tbody>
</table>

* Pillai’s trace F-Value was used for the among subject effect.
4.3.4. Effectiveness of protective socking material against predation by diving ducks

The two-way analysis of variance on the proportion of dry mussel biomass lost to predation in Brackley Bay in 2003 revealed an interaction between size and sock type (df= 2, 4, F= 21.55, p= 0.0072), so the analysis was recoded into a one-way ANOVA with six treatments. Large mussels were not preyed upon, and the effectiveness of the protective socking material against predation by Greater Scaup differed between small and medium mussels (Figure 4.6; df= 5, 10, F= 82.30, p< 0.0001). *A posteriori* comparisons revealed that the protective material did not reduce the proportion of small mussels lost to predation compared with the regular material during spring 2003. However, the protective material did reduce losses of medium mussels. Predation was most severe on small mussels and medium ones socked in the regular material. Medium mussels in protective material were preyed upon less than the previous, but more than the large mussels.
Figure 4.6 Mean proportion of mussel biomass lost ± SE to Greater Scaup predation in the different sock combinations of experimental culture site. Three mussel size categories and two sock types, regular and protective (Reg and Pro), were used. Means with the same letters are not significantly different under $\alpha = 0.05$. 
4.3.5. Biodegradation of the protective layer

Calibration of the homemade tensiometer revealed a linear relationship between spring elongation and weight resistance (df= 1, 19, F= 2454.26, p< 0.0001, R²= 0.9923); spring elongation = 0.1226*weight resistance.

Results of the three-way ANOVA on strength of socking material in all three bays (Figure 4.7; Oct 02 to May 03), revealed an interaction between site, size and date (df= 8, 24, F= 3.66, p= 0.0064), so the analysis was rerun by size. The strength of the protective layer of socks containing small and large mussels decreased in time (small: df= 2, 6, F= 49.99, p= 0.0002; large: df= 2, 6, F= 62.29, p< 0.0001), and was consistent among sites (small: df= 2, 12, F= 3.60, p= 0.0597; large; df= 2, 12 F= 1.80, p= 0.2065). The effect of date on the strength of the protective layer of socks containing medium mussels was influenced by site (df= 4, 12, F= 4.05, p= 0.0264), so the analysis for this section was recoded into a one-way ANOVA with nine treatments and a posteriori comparisons were carried out. A treatment effect was observed in the model (df= 8, 18, F= 27.14, p< 0.0001). Comparisons revealed that the strength of the protective layer in socks containing medium mussels generally declined in time while remaining consistent among sites (Table 4.5).
Table 4.5: Tukey’s *a posteriori* comparisons on the strength of the protective layer of socks containing medium mussels. Means with the same letter are not significantly different.

<table>
<thead>
<tr>
<th>Tukey’s grouping</th>
<th>Mean</th>
<th>N</th>
<th>Site</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2.6562</td>
<td>3</td>
<td>Brackley</td>
<td>Oct 02</td>
</tr>
<tr>
<td>a</td>
<td>2.6562</td>
<td>3</td>
<td>New London</td>
<td>Oct 02</td>
</tr>
<tr>
<td>a</td>
<td>2.6562</td>
<td>3</td>
<td>St. Peter’s</td>
<td>Oct 02</td>
</tr>
<tr>
<td>b, a</td>
<td>2.5656</td>
<td>3</td>
<td>Brackley</td>
<td>Jan 03</td>
</tr>
<tr>
<td>b, c</td>
<td>2.5133</td>
<td>3</td>
<td>New London</td>
<td>Jan 03</td>
</tr>
<tr>
<td>b, c, d</td>
<td>2.4817</td>
<td>3</td>
<td>St. Peter’s</td>
<td>Jan 03</td>
</tr>
<tr>
<td>c, d</td>
<td>2.4013</td>
<td>3</td>
<td>Brackley</td>
<td>May 03</td>
</tr>
<tr>
<td>c, d</td>
<td>2.4286</td>
<td>3</td>
<td>New London</td>
<td>May 03</td>
</tr>
<tr>
<td>d</td>
<td>2.4382</td>
<td>3</td>
<td>St. Peter’s</td>
<td>May 03</td>
</tr>
</tbody>
</table>

The strength of the protective layer from mussel socks in New London Bay and St. Peter’s Bay (Figure 4.7; Oct 02 to Aug 03) declined in time (df= 3, 8, F= 65.88, p< 0.0001) and was consistent among sites (df= 1, 8, F= 0.22, p= 0.6520). Strength was, however, different between socks containing different mussel sizes (df= 2, 16, F= 16.90, p= 0.0001). *A posteriori* comparisons revealed that the protective layer of socks containing small and medium mussels was more resistant than the protective layer of socks containing large mussels.
Figure 4.7 Mean weight resistance ± SE of threads from the protective layer of socking material in time, for socks containing mussel of different seed size category reared in three P.E.I. bays.
Mean weight resistance (g) ± SE

Small

Medium

Large

Site

Brackley  New London  St.Peter's

Oct 02  Jan 03  May 03  Aug 03
4.4. Discussion

4.4.1. Mussels lost to predation by diving ducks during fall 2003

Although many diving ducks were present in the study areas during the fall staging period, no predation was detected in either experimental site (Table 4.2). Mussel densities of the different treatment combinations in both sites remained unchanged from October 2002 to January 2003, with or without exclusion cages, except for the large mussels in New London Bay. Sampling revealed that the density of the large mussels socked in the protective material increased over time for treatments and controls. Potential explanations for this apparent increase include sampling error, but also the different mussel seed sources used for socking. During the socking process, mussel seeds from another location had to be used to supplement in New London Bay’s experimental site. If the seeds from the second source were different in size, then the socking densities would be different. The polypropylene sleeve is not elastic, so volume is fixed. If smaller seeds were used, for example, the mussel socking density would increase.

Mussel density among sock types was also different, all sizes pooled, in Brackley Bay, and in each size in New London Bay. Mussel density was higher in the protective materials compared with the regular ones. Differences between socking materials probably occurred when socks were put in the water. Before being hung, the mussel socks were soaked over night in running water so mussels could begin attaching to the sock and each other. However, mussel attachment is still not very strong following this
process, and many are lost when socks are hung on the long-lines. The protective material has a second layer with smaller mesh openings, which could have reduced the initial losses associated with sock manipulation.

4.4.2. Migration of mussels through the different socking materials during fall 2003

The protective socking material significantly reduced migration of large mussels in both experimental culture sites. Compared with the regular material, the protective socks retained about two times more mussels inside the socks. Mussels inside the socks are considered less vulnerable than those outside because the sock layer offers physical protection against predation by diving ducks. Regular mussel socks that were preyed upon early in the fall, in a nearby commercial lease, have been observed to "rebound" later thanks to the mussels left inside the socks (B. Andrew, mussel grower, pers. com.). Because mussels were preyed upon early in the season, migration of mussels outside the socks was only partial. Most of the losses seemed to have occurred in the migrated mussels, since no damage was observed on the socking material itself. Predation gaps in the migrated mussels were unnoticeable the following spring as the mussels that were still inside at the time replaced them. Mussels inside the socks were therefore less vulnerable.

The protective material also reduced migration of medium mussels in Brackley Bay only. The protective socking material retained about 10% more mussels than the regular material. Protection for medium-sized mussels is considered to be minimal, because of
the small difference in migration between the two sock types and because this difference was not consistent across experimental sites. The protective material in either site did not restrain migration of small mussels. Physical characteristics of the protective layer can explain why it was largely ineffective. Mesh openings of the protective layer were probably too big or stretchable to significantly reduce migration of small and medium mussels compared with the regular material.

Mussel migration rate through mussel socks in Brackley Bay was affected by sock type for small mussels only. Surprisingly, migration of the small mussels was higher in the protective socking material compared with the regular material. These results are probably due to the fact that density of small mussels socked in the protective material was about 25% higher than in the regular material. If there are more mussels and the protective layer does not restrict migration, then more mussels would be expected to come out. This difference did not occur in New London Bay, probably because the overall density of small mussels was about 45% lower than in Brackley Bay, reducing the need for mussels to push out in order to filter feed. Small mussel densities were lower in New London Bay because mussels were bigger than those in Brackley Bay. As socking density increases, competition for food, space and oxygen will also increase (Mallet and Myrand 1995). Mussels located in the inside of socks will suffer a reduced water flow and competition for food and oxygen with mussels located outward. Density will therefore affect mussel movement, as they compete for the optimum location to grow out.
A cage effect was observed for medium mussels in New London Bay. However, this was the only time a cage effect was noted. This effect could be the result of a sampling error, or the fact that a different source of mussels had to be used to complete the experimental set up. As in the case of section 4.4.1. (increase in mussel density over time for large mussel in protective material), similar socks probably contained mussels of different sources, and these might not have been of the same size, therefore affecting the socking densities and mussel migration.

4.4.3. Effectiveness of protective socking material against predation by diving ducks

The protective socking material reduced mussel predation by diving ducks for medium size mussels only, during spring 2003, in Brackley Bay. The medium size mussels socked in the regular material suffered more damage by Greater Scaup than those socked in the protective material. The regular material lost on average 77% of its dry biomass, while the protective material lost on average 46%. This 40% difference is surprising since there were only 13% more migrated mussels in the regular material in January 2003. It is possible that mussel migration in the regular material was underestimated when sampling underwater because of lack of contrast between the black socks and the dark mussels. It is also possible that mussels in the regular material kept coming out faster than in the protective material, as the protective layer was still present and strong, and that the difference in migrated mussels increased from January 2003 to May 2003.
The protective material did not reduce predation of small mussels as protected socks lost as many mussels as the regular socks. These results are consistent with estimates of mussel migration for small mussels. The protective material did not reduce migration of small mussels.

Predation on the large mussels was also not affected by the protective socking material. Although Greater Scaup were capable of eating large mussels (Section 3.3.3), data suggest that they ignored this size category. A size selection experiment conducted at the same time using mussels from the same source revealed that large mussels were the least preferred size category (Section 3.3.2.3). Many studies have shown that diving ducks prefer small mussels (Draulans 1982, 1984; Nyström and Pehrsson 1988; Bustnes and Erikstad 1990; De Leeuw and Van Eerden 1992; Guillemette 1994; Bustness 1998; De Leeuw 1999; Hamilton 1999). Therefore, because ducks largely avoided the largest mussel size class, it was impossible to assess the effectiveness of the protective material as a deterrent to duck predation on this type of seed. However, given that a higher proportion of large mussels were retained inside socks than observed for medium seed, it is reasonable to speculate that the protective material would have performed somewhat better for this class than for the other mussel sizes in the study.

The initial intended use of the protective socking material was to protect cultivated mussels during the fall predation period and then biodegrade before spring, when growth accelerates. Unfortunately, no predation occurred during the fall period. However, if we consider that mussels inside the stocking material were less vulnerable than those outside, results would have been similar, because migration was reduced only for large
mussels in both sites and medium mussels in Brackley Bay. Because the protective layer was still present and strong during the spring staging period, this experiment is still a good indication of the effectiveness of the protective socking material against predation by diving ducks. If predation had occurred during the fall, the contrast between the different treatments in damage observed would have been similar, but the total amount of mussels lost may have been lower, because fewer mussels were vulnerable.

4.4.4. Biodegradation of protective layer

Strength of the threads composing the cotton-polyester layer in the protective socking material initially declined by 25 to 30% (October 2002 to January 2003), and this was consistent among sites. Degradation of the protective layer then seemed to level off. The initial quick drop is presumably due to the disappearance of the cotton part of the material, which is not as resistant as the polyester. Biodegradation of the protective layer is presumably linked to the bacterial activity in the water. Detrital substances known as particulate organic matter (POM) form the substrate for bacterial growth (Barnes and Hughes 1999). However, when comparing resistance of the material for socks containing different mussel sizes (sites pooled) in New London and St. Peter’s Bay (from October 2002 to August 2003), it seems that socks containing large mussels had weaker threads than the others. These differences could be attributed to the action of mussel migration. The protective socking material reduced migration of the large mussels in all sites. Some of those that migrated out of the regular sleeve were partially stopped by the protective layer. Although some mussels were trapped between the two layers, those still inside the regular layer kept pushing out, stretching the protective layer. This action could have
cause an additional stress on the cotton-polyester threads, making them weaker for large mussels. The medium and small mussels were not constrained by the protective layer, therefore reducing the additional stress of mussel migration caused by a build up in between the two layers.

The biodegradation of the protective layer was slower than expected. The cotton-polyester layer was supposed to be gone by the following spring in order not to restrict mussel positioning and filter feeding. Mussel growth is related to external factors such as food availability and water temperature (Mallet and Myrand 1995). A growth experiment conducted on the same mussels in the same place revealed that the majority of the growth takes place when the water heats up and its productivity increases, from mid spring through the fall period (Lauzon-Guay 2004). Lauzon-Guay (2004) also compared growth of mussels between the regular and the protective socking material. He found that mussels trapped inside the protective socking material had a lower growth rate, and this reduced the overall mean growth of mussels from the protective socks compared with those from regular socks. Mussels trapped inside probably had a lower growth rate because of reduced water flow and depleted levels of food and oxygen. Mussels located on the edge act as a barrier against the water flow and deplete the water of food and oxygen. Different proportions of cotton and polyester in the protective layer are therefore needed so that the protective layer disappears by springtime, not restricting growth of mussels.

The fact that the protective layer remained strong during the high growth period also created some unexpected deformations on a small proportion of mussels (Figure 4.8). Threads from the protective material created an opposing force, and when the mussels
grew, this caused dents near the mouth of up to 10% of them (pers. obs.). Although this represents a small proportion of mussels, these deformed mussels become unsuitable for the market, reducing yields for mussel growers.
Figure 4.8 Mussel malformation induced by the protective layer of the protective socking material.
4.4.5. Management implications or industry related issues

The protective socking material represent a potential peaceful solution to reduce mussel losses to diving ducks. Some work is still needed to determine the ideal mesh size of the protective layer to reduce mussel migration for small and medium seed sizes. A new blend of cotton and polyester also needs to be tested to ensure that the protective layer biodegrades on an appropriate time scale (i.e., by the following spring when mussel growth rates accelerate). Although results were fairly consistent in the different bays of PEI, degradation speed of the material could be different in other parts of the world, and specific tests should carried out before using this material. Currently, this protective socking material is about 20 times more expensive than the regular material, and the costs makes it impossible for growers to use it economically. However, the material is not yet produced on a commercial basis, which could lower production costs. If we take into account the cost of scaring, the increasing mussel losses and eventually a better price for the protective socking material, a modified form of the protective material could become an efficient and peacefully way of reducing losses to diving ducks, and permit coexistence of ducks and mussel growers.

4.5. Bibliography


Meixner, R. 1986. The predation of mussels by eiders (Somateria mollissima) and its’ effect on German mussel farming. ICES: 28.


5. General conclusion

Cultivation of blue mussels in Prince Edward Island (P.E.I.) started in the 1970’s on an experimental basis. As the market for cultivated mussels and culture techniques evolved, so did the industry, reaching a point where most of the Island’s suitable areas are currently being used (Thompson and Gillis 2001). Reports of predation by diving ducks on the Island’s mussel farms started in 1993, but no formal quantification of these interactions had been conducted.

Losses to diving ducks can threaten the viability of mussel culture operations, but also, many North American diving duck species are in a continental decline (Sea Duck Joint Venture Management Board 2001), and any additional disturbances from aquaculture activities during the staging period could be detrimental to waterfowl populations. The objective of this research was to study the relationship that exists between diving ducks and cultivated mussels in P.E.I. in order to quantify effects of this interaction on both parties. Specifically: 1) I analysed existing aerial survey data from the Canadian Wildlife Service (CWS) on the historical numbers and distribution of the two duck species (Greater Scaup and Long-Tailed Duck) in relation to the development and the intensity of mussel aquaculture; 2) using experimental mussel culture sites, I studied the foraging behaviour of Greater Scaup when feeding on cultivated mussels, as well as quantifying losses for growers; 3) using the same culture sites, I tested the potential of the protective socking material as a deterrent against predation by diving ducks.
Although there is no direct evidence that the two main migrating waterfowl species have benefited from cultivated mussels, abundance of Greater Scaup and Long-Tailed Duck in P.E.I. during the fall staging period has increased as the mussel industry expanded (Figure 2.2). Cultivated mussels represent an abundant and high quality food resource available for waterfowl. Many studies have showed that food resources can regulate waterfowl abundance (Milne 1969; Pehrsson 1984; Van Eerden 1984; Stanczyskowska 1990; Wormington and Leach 1992; Gardarsson and Einarsson 1994; Larsen and Guillemette 2000). Populations of diving ducks could benefit from this new food resource, acquiring the necessary fat reserves to pursue migration and for the over wintering period. Feeding on cultivated mussels could also reduce the costs of foraging because they are more abundant, easy to find, are present in shallower depths and have higher tissue:shell ratio than wild mussels (Dunthorn 1971). The presence of cultivated mussels could also affect migration patterns of diving ducks. Diving ducks have altered their migration patterns and shifted their staging location in response to the zebra mussel invasion in Europe (Geroudet 1966; Pedroli 1981, 1982) and North America (Wormington and Leach 1992; Hamilton and Ankney 1994).

An increase in abundance of both species took place in areas where mussel culture was the most intense. Based on the historical distribution, Long-Tailed Ducks seem to have been specifically attracted to cultivated mussels (Figure 2.6). Long-Tailed Ducks are sea ducks, which do not typically stage in sheltered bays (Bellrose 1980). Prior to mussel aquaculture, they were present in small numbers in the different areas that eventually harboured different levels of mussel aquaculture. Greater Scaup, on the other hand, are bay ducks and prefer sheltered waters (Austin et al. 1998). They were historically
abundant in areas were mussel aquaculture eventually became the most intense (Figure 2.5). Therefore, although populations of Greater Scaup could have responded to cultivated mussels, other habitat characteristics could have influenced their distribution. Although diving ducks in general could benefit from the presence of cultivated mussels, there are also associated disturbances that could offset profitability of this food source. New studies are needed to evaluate if related aquaculture activities and scaring techniques reduce the ability of staging waterfowl to acquire the necessary fat reserves. This study also highlights the importance of acquiring historical data. None of these results could have been achieved without these data. As human activities continue to change the landscape, it is important to acquire baseline data on wildlife and their habitats in order to properly assess the impacts of our various activities.

Greater Scaup were size-selective predators when feeding on cultivated mussels (Figure 3.2). Although they were capable of eating large mussel seeds, ducks selected the smaller size categories. Analysis of mussels showed no support for the shell mass minimisation hypothesis (Figure 3.3). Contrary to those of Bustnes and Erikstad (1990), Bustnes (1998) and Hamilton et al. (1999), results of this study showed that the dry tissue:shell ratio increased with mussel size. Integration of other important factors such as intake rate and costs of processing mussels shells and excess salt (Nyström and Pehrsson 1988; De Leeuw 1999) could explain why ducks did not select mussels with the relatively higher tissue content. Foraging costs in diving ducks are high (Woakes and Butler 1983; Van Eerden and De Leeuw 1992; De Leeuw 1999; Nehls 2001), so in order to optimize foraging, ducks need to minimise costs as well as maximizing gains.
(Guillemette 1994). Also, profitability of mussels was calculated on an individual mussel basis. Estimates of profitability should be considered on a foraging bout basis in order to take into account the multiplicative effect of filling up on mussels of different sizes. Studying the foraging behaviour of diving ducks in the wild can be very difficult, especially when trying to integrate multiple factors in profitability estimates of prey. Experiments with captive birds should be considered, for logistic reasons and because of the importance of calculating costs related to processing mussels.

Large mussels in my experiments were almost completely avoided. However, in the commercial culture site, small mussel seed sizes were absent and ducks ate large mussels (Table 3.1). Although ducks will avoid the larger mussels, as small ones are depleted they eventually shift to eating larger prey. Also, Greater Scaup and Long-Tailed Duck are relatively small diving duck species and the size of mussels consumed is therefore limited. After six to eight months mussels reach a certain size, making them unavailable for the two main diving ducks species. Larger sea ducks (e.g., eiders) have also been reported on the island during the fall and spring migration. This species is capable of eating larger mussels, up to the minimum commercial size (about 55 mm). If their staging populations increased or distributions shifted, the number of mussels vulnerable to predation would dramatically increase.

The protective socking material was only partially effective against duck predation (Figure 4.6). It reduced predation somewhat of medium-sized mussel seed only. Because mesh openings of the protective layer were too large, small mussels migrated out of the protective socking material at the same rate as in the regular material, making them
equally vulnerable (Figure 4.5). Also, the protective layer did not biodegrade fast
even to disappear in time to allow for optimal growth conditions the following spring.
Larger mussels were still partially trapped in between layers, potentially reducing the
ability of mussels to filter feed. Although the protective socking material did not meet
expectations, its potential as an effective deterrent remains.

Modifications in the mesh openings and blend of the protective layer need to be made to
ensure the proper mix of protection and biodegradability. Particular characteristics of a
protective socking material need to be determined in relation to the location of use, as
mussel seed sizes used and degradation of the protective layer may vary from one place
to another. Currently, the protective socking material costs about 20 times more than the
regular material, making its use unprofitable for mussel growers. The product is made on
an experimental basis and more efficient production methods have yet to be developed.
However, interactions between diving ducks and cultivated mussels are expected to
increase. A higher demand for this product could result in commercialization and
reduction of costs, making it a viable alternative for growers.

Findings from this project could be applicable in other parts of the world where
interactions between diving ducks and cultivated mussels occur. Results of this study
could also contribute to sustainable development of the mussel industry, and bring useful
information to help in the management of our coastal waters.
5.1. Management implications

This study also yielded basic information on simple culture site management techniques that could help reduce the risk of ducks inflicting serious losses on mussel farms.

1) Using only the large mussel seeds could reduce losses, because ducks prefer smaller mussels. However, most ducks can consumed the larger mussel seed sizes and growers depend on wild mussel recruitment for their seeds. Wild seed stocks are highly variable in number and size structure from year to year, and growers must use what they have. I have often seen growers discarding a fourth and smaller seed size, the pepper seed. Socking these small mussels often results in excessive densities, which in turn creates major crop losses during the summer when water temperature is high and oxygen levels are low. Instead of using these mussels as part of the regular crop on a mussel line, they could be added in between other socks, luring the ducks away from socks with quality mussel seeds.

2) Socks containing the smaller or more vulnerable mussel seeds should be positioned in area of culture leases where natural disturbances are highest. Placing seed lines (source of mussels) and socks containing the smaller mussels near a wharf, a road or in the vicinity of other fishing activities could make the area less attractive to ducks and avoid predation. Ducks are nervous animals and will avoid areas of high disturbances in general.
3) Sinking the buoys that hold the mussel lines below water could also help reduce the probability of ducks identifying the resource. Feeding on cultivated mussels appears to be a learned behaviour (Burnett et al. 1994), and ducks could very well have associated the presence of buoys with available mussels. Also, series of buoys can resemble a flock of ducks from a distance. They could therefore act as lures for ducks flying by, in the same way as hunting decoys.

4) Location of a culture lease is probably very important. Establishing a culture site away from areas where diving ducks are known to stage, nest or overwinter could reduce the probability of losing mussels. Minimum distances to keep should be specific to each location, because they will depend on the ecology of the different species of ducks involved and their state (migrating, nesting or over wintering). These will affect the maximum distance a bird is willing to travel to forage (Burnett et al. 1994). This option is, however, probably not feasible in P.E.I. given that most of the Island suitable are currently being used.

5) Losses could also be reduced by socking as late as possible or by socking in vulnerable areas last. Late in the socking season, the water is colder and migration of mussels outside the sock is slower. The majority of the mussels would remain inside the sock until ice covers the bay. The sock itself could act as a barrier against predation by diving ducks, potentially reducing losses.

6) As soon as ducks have been observed feeding on cultivated mussels, conventional scaring techniques should used as quickly as possible in order to discourage ducks from
adopting the site as a foraging ground and to prevent them from learning to feed on cultivated mussels. Once ducks learn to feed on this profitable resource, it might prove to be very difficult to stop them. Waterfowl species that stage in P.E.I. endure severe conditions throughout their life cycle, and they are capable of surprising behavioural adaptations in order to forage and meet their daily energy requirements.

### 5.2. Bibliography


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Dionne, M., Hamilton, D.J., Diamond, A.W. Relationship between diving ducks and mussel aquaculture in Prince Edward Island, Canada. Poster presentation at the 122nd stated meeting of the American Ornithologists’ Union, August 2004, Quebec, QC.


