DIET-DEPENDENT EFFECTS OF DIGESTION ON METABOLIC RATE OF CLEARNOSE SKATES (*Rostroraja eglanteria*)

by

Hunter Christensen

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Bachelors in Marine Science with Distinction

May 2025

© 2025 Hunter Christensen
All Rights Reserved

DIET-DEPENDENT EFFECTS OF DIGESTION ON METABOLIC RATE OF CLEARNOSE SKATES (*Rostroraja eglanteria*)

by

Hunter Christensen

Approved: _____

Aaron Carlisle, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved: _____

Joanna K. York, Ph.D.
Committee member from the School of Marine Science and Policy

Approved: _____

Matthew Oliver, Ph.D.
Committee member from the Board of Senior Thesis Readers

Approved: _____

Sarah Trembanis, Ph.D.
Chair of the University Committee on Student and Faculty Honors

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Aaron Carlisle for giving me the opportunity to work in the T.R.A.S.E.R. lab. I would also like to thank University of Delaware graduate students Scott Goldberg, Tess Avery and Andrea Leontiou, who were a tremendous help in this research project. Your guidance was not only necessary for me to carry out my research project, but it has also allowed me to grow as a student and learn what it means to be a scientist. I could not have done the amount of work it takes to do research if it weren't for the helping hands of my fellow undergrads Trinity Clifford, Ahmad Crawford and Kristin Lewis. Lastly, thank you to my family for supporting me throughout my undergraduate experience.

TABLE OF CONTENTS

ACKNOWLEDGMENTS iii
LIST OF TABLES v
LIST OF FIGURES vi
ABSTRACT viii

1 INTRODUCTION 1

2 METHODS 5

3 RESULTS 8

4 DISCUSSION 12

5 CONCLUSION 17

REFERENCES 18

A TRIAL DATES 20
B RAW DO% VALUES 21

LIST OF TABLES

Table 1 Pre-feeding metabolic rates, peak post-feeding metabolic rates, % increase and time of peak associated with the mass of prey eaten for each type. 11

Table 2 Energy expended by SDA (in mgO_2/kg and kJ) versus energy ingested (in kcal and kJ). The ratio of kJ ingested:kJ expended is provided as a quotient. 11

Table 3 Trials and dates when each was conducted. 20

LIST OF FIGURES

Figure 1 Metabolic rates of two Clearnose Skates fed on anchovy and shrimp. Each data point represents the average metabolic rate over a two hour interval. The vertical line at time=0 represents when the skates were fed. Rates to the left of the vertical line are the RMR of fasted skates. Standard error for each metabolic rate is included in appendix B. 9

Figure 2 Increase in metabolic rate of the two skates after being fed anchovy and shrimp. These values are the peak MO_2–fasted MO_2 for each trial.. 10

Figure 3 Raw dissolved oxygen % values between each flush for Skate 1's shrimp trial. Replicate 1 of 5 was used to measure fasted RMR. Replicates 2-5 were after feeding. DO% Values in the red shaded area were omitted to exclude elevated DO% measurements from the flush. Values after time=120 in replicate 1 of 5 were excluded from metabolic rate and from standard error because the respirometer was open for feeding. Standard errors for the regression line were 4.922632E-06, 3.190816E-06, 3.044123E-06, 1.788360E-06 and 2.519727E-06 for replicates 1-5 respectively. 21

Figure 4 Raw dissolved oxygen % values between each flush for Skate 1's anchovy trial. Replicate 1 of 5 was used to measure fasted RMR. Replicates 2-5 were after feeding. DO% Values in the red shaded area were omitted to exclude elevated DO% measurements from the flush. Values after time=120 in replicate 1 of 5 were excluded from metabolic rate and from standard error because the respirometer was open for feeding. Standard errors for the regression line were 2.831310E-06, 4.454407E-06, 3.502960E-06, 2.793488E-06 and 3.302266E-06 for replicates 1-5 respectively. 22

Figure 5 Raw dissolved oxygen % values between each flush for Skate 2's shrimp trial. Replicate 1 of 6 was used to measure fasted RMR. Replicates 2-6 were after feeding. DO% Values in the red shaded area were omitted to exclude elevated DO% measurements from the flush. Values after time=120 in replicate 1 of 6 were excluded from metabolic rate and from standard error because the respirometer was open for feeding. Standard errors for the regression line were 9.422209E-06, 2.859898E-06, 1.077508E-05, 6.632956E-06, 4.333461E-06 and 5.480169E-06 for replicates 1-6 respectively. 23

Figure 6 Raw dissolved oxygen % values between each flush for Skate 2's anchovy trial. Replicate 1 of 5 was used to measure fasted RMR. Replicates 2-5 were after feeding. DO% Values in the red shaded area were omitted to exclude elevated DO% measurements from the flush. Values after time=120 in replicate 1 of 5 were excluded from metabolic rate and from standard error because the respirometer was open for feeding. Standard errors for the regression line were 4.598448E-06, 3.234875E-06, 2.088154E-06, 3.976540E-06 and 2.016906E-06 for replicates 1-5 respectively. 24

ABSTRACT

This study aimed to describe the impact of diet on specific dynamic action (SDA) in Clearnose Skates (*Rostroraja eglanteria*). Metabolic rates of mature female Clearnose Skates (n=2) were calculated before and after being fed anchovies and shrimp. Metabolic rates were measured using static respirometry. Skates had an increase of up to 1.68x pre-feeding MO_2 when eating anchovy, and an increase of up to 1.31x pre-feeding MO_2 when eating shrimp. Meal size was also found to increase the duration and peak of the SDA effect. Minimizing the amount of energy occupied by SDA makes feeding more efficient and provides more available energy for Clearnose Skates.

Chapter 1

INTRODUCTION

Metabolic rate is the amount of energy an animal uses per unit time. Standard metabolic rate (SMR) is the basal metabolic rate, as it includes only the rate of ATP usage to sustain life in an animal. Routine metabolic rate (RMR) includes the energy required for routine movement and spontaneous activity (Killen et al. 2021). For water breathing animals such as fishes, the primary way that we measure metabolic rate is through respirometry. Respirometry uses the animal's oxygen consumption (MO_2) as a proxy for metabolic rate. Many factors influence metabolic rate in a species such as size, age, sex and environmental conditions like temperature and salinity (Zhao et al. 2025). SMR can increase temporarily as animals use more energy for temporary processes like digestion.

The energetic cost of digestion is called specific dynamic action (SDA). SDA reflects the combination of processes associated with feeding and digestion, such as the mechanical and chemical breakdown of food in the stomach and intestine, absorption of nutrients across the intestinal walls, and peristalsis. The magnitude of SDA is dependent on the composition of macronutrients in the food being digested. For example a low-protein, high-carbohydrate diet resulted in a significantly lower peak in postprandial MO_2 when compared to other diets in the Southern Catfish (*Silurus meridionalis*) (Fu et al. 2005). Similarly, when feeding different diets to the Pearl Spot (*Etroplus suratensis*), increases in MO_2 ranged from 46.47% to 129.56% higher than pre-feeding MO_2 (Somanath et al. 2000). This means that some dietary

items require more energy to digest and assimilate than others. Minimizing the energetic cost of digestion essentially makes feeding more efficient. Every animal has a bioenergetic budget, which is how it allocates all of its available energy for different essential biological functions such as digestion, locomotion, respiration, growth, and reproduction. While SDA is one of many factors that influences the amount of energy an animal uses, reducing the cost of digestion will reserve more energy for the animal's growth and/or reproduction (Grayson et al. 2005).

SDA is quantified by measuring the increase in an animal's metabolic rate after feeding. SDA can either be characterized by the peak post-feeding metabolic rate, or by the magnitude, which is the total mgO_2/kg consumed during the duration of SDA. A typical SDA study will find the magnitude by taking the area under the SDA curve, bound by SMR (Chabot et al. 2016). The duration of SDA and the time at which the peak occurs can vary. Because different macronutrients (i.e., protein, lipid, carbohydrates) have different energetic content and vary in ease of digestion, the relative magnitude of SDA will vary across different prey. Protein has a greater influence on post-feeding oxygen consumption than lipids and carbohydrates in fishes (Fu et al. 2005; Amos & William H. 1980). This is likely because protein is made up of complex amino acid chains which require more energy to break down than fat tissue and carbohydrates. The size of a meal can also have an effect on SDA peak and duration (McGaw and Curtis 2013; Wang et al. 2012).

The Clearnose Skate is one of the most abundant elasmobranchs in the Delaware Bay, but few studies focus on this animal's ecological impact. They hold an

important place in the Delaware Bay food web by providing top-down control of populations at lower trophic levels. Clearnose Skates are benthic mesopredators which feed on a variety of prey including decapod crustaceans, squid, bivalves and small fish. Decapod crustaceans are the most common prey found in the stomachs of Clearnose Skates, with the most abundant species of which being the shrimp *Crangon septemspinosa* (Szczepanski 2013). There are at least 31 different species included in their diet, with teleost fishes and cephalopods being some of the less common prey. As generalist predators there is a lot of variation in macronutrients such as fat and protein in their diet. It's unclear how variation in their diet affects their bioenergetic budget. Additionally, by determining how much energy Clearnose Skates need for each part of their bioenergetic budget we can ultimately estimate how much energy they need, i.e. how much they need to eat. This can inform management decisions for Clearnose Skates and the populations of their prey.

In this study, we measure the effect of SDA on Clearnose Skate metabolic rate across two different diets to 1) quantify the magnitude of SDA for this species, and 2) understand how dietary composition impacts SDA. We used shrimp and anchovy as the two diet treatments, since they are relevant prey for skates and differ in macronutrient content. By using literature values for protein, lipid and carbohydrate composition for each we can associate certain nutrients with their relative impact on skate metabolism. Relating SDA to the macronutrient composition of food allows us to better understand how variation in diet of Clearnose Skates may impact their bioenergetics in the field. I hypothesized that digesting shrimp would cause a greater

increase in metabolic rate because shrimp are generally expected to have a higher protein content than anchovy (Soriguer et al. 1997). The effect of meal size on SDA parameters was also investigated. I expected a larger meal size to result in a greater SDA peak and duration in Clearnose Skates.

Chapter 2

METHODS

Skates were collected from the Delaware Bay using an otter trawl and transported to the UD Sharp Campus. Skates were kept in tanks with a salinity of 30–35 at 22 ± 0.5°C. The two skates that we tested in this study were females with total lengths of 68.5 and 67.5 centimeters. Female Clearnose Skates reach sexual maturity between 59 and 65 cm total length (Sosbee 2005). Thus the test subjects were mature females, also evidenced by them dropping egg casings during regular husbandry. Dates of each experimental trial are included in Appendix A.

We used intermittent-flow static respirometry to measure metabolic rate in skates. The respirometer (480 liters) was filled to the rim with seawater at 22 ± 0.5°C, and equipped with a YSI oxygen probe and a mixing pump to circulate water in the respirometer, ensuring that the entire tank was well mixed. An inflow and an outflow valve was used to flush the respirometer with oxygenated water from a flush tank. For each trial a plexiglass lid was clamped to the top of the respirometer to seal it, preventing oxygen diffusion from the air. Since skates were free to move around the respirometer, the metabolic rates we obtained were routine metabolic rates (RMR).

We weighed each skate using a hanging scale before putting them in the respirometer for acclimation. Skates were acclimated for 10–14 hours before their metabolic rates were measured. This allows the skates to become comfortable with the experimental setup overnight to ensure their metabolic rates aren't elevated by stress during trials. The mixing pump remained on during acclimation to match the testing

conditions. Each skate was fasted for at least 7 days before trials to ensure their digestive tracts were completely empty and there would not be any SDA effect. This is consistent with fast times and SDA durations in experiments on other elasmobranchs (Sims and Davies 1994; Chen et al. 2008). We prepared both food types by thawing them and cutting them into smaller pieces to ensure that the skates would eat voluntarily in the respirometer. The exoskeleton and appendages were removed from shrimp before being fed to the skates.

During respirometry trials, we used a YSI to record the dissolved oxygen concentration in the respirometer every minute for the duration of the trial (11 hours during the daytime). The first two hours of oxygen measurements prior to feeding the skate were used to obtain RMR without any influence of SDA. After two hours the lid was opened and the skates were fed 6% of their body mass, or until satiation, and then the lid was sealed while oxygen consumption was continuously recorded. In trials where the skate did not eat all 6% of its body mass, the excess food was removed and weighed before resealing the lid to obtain the mass of food eaten by the skate. We flushed the respirometer with oxygenated water every two hours during the trial to ensure the dissolved oxygen content of the water never decreased below 80%. In the event that the dissolved oxygen dropped below 80%, we performed an early flush after just one hour so the skate's safety was not at risk. This happened once during Skate 2's shrimp trial, and as a result two of the average metabolic rates measured were over one hour instead of two (Appendix B). Dissolved oxygen values were omitted for the first 25 minutes after each flush to account for the time it takes the circulation pump in

the respirometer to mix the water until homogenous. After each trial we removed the skate, resealed the respirometer, and recorded oxygen concentration again for two hours to calculate background respiration in the system (control). Metabolic rates were calculated and adjusted by the background rate of respiration using the respR package in Rstudio. The area under the curve of metabolic rates greater than pre-feeding RMR was taken to calculate SDA magnitude for the first 8 hours after feeding. Oxygen consumption was converted to energy using a conversion rate of 13.84 J mgO_2^{-1} (Fu et al. 2005; Wang et al. 2012).

Chapter 3

RESULTS

The peak metabolic rate was higher in both skates after eating anchovies compared to shrimp (Figure 2). The peak occurred between 0 and 4 hours after feeding in all four trials. Greater meal size resulted in a greater increase in MO_2 under the anchovy treatment (Table 1). Meal size was positively correlated with SDA duration, as post-feeding MO_2 returned to a pre-feeding rate 6–8 hours after a meal of 2.2% body mass (Figure 1). SDA duration was >8 hours in the remaining trials. Meal type impacted SDA magnitude in Skate 1, with SDA values of 283 mgO_2/kg and 786 mgO_2/kg when digesting equal masses of shrimp and anchovy respectively (Table 2).

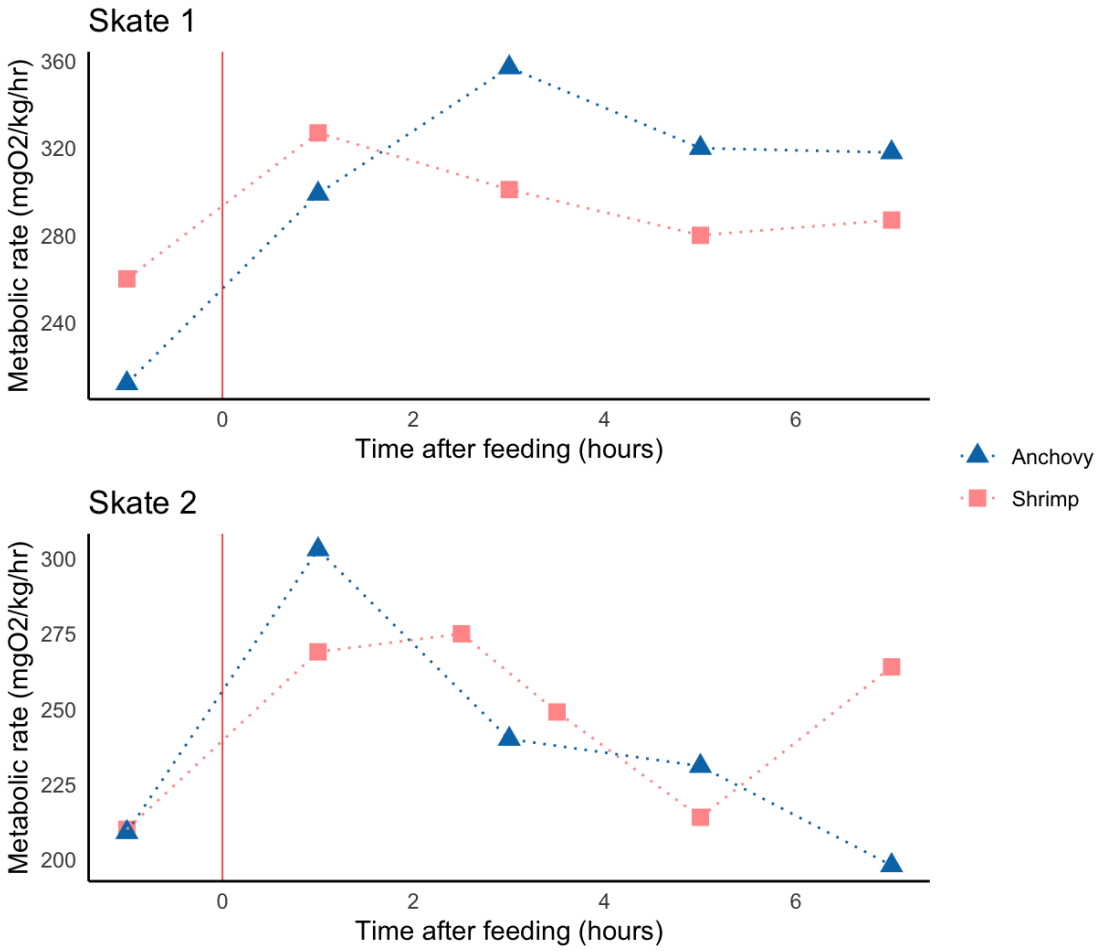

Figure 1 Metabolic rates of two Clearnose Skates fed on anchovy and shrimp. Each data point represents the average metabolic rate over a two hour interval. The vertical line at time=0 represents when the skates were fed. Rates to the left of the vertical line are the RMR of fasted skates. Standard error for each metabolic rate is included in Appendix B.

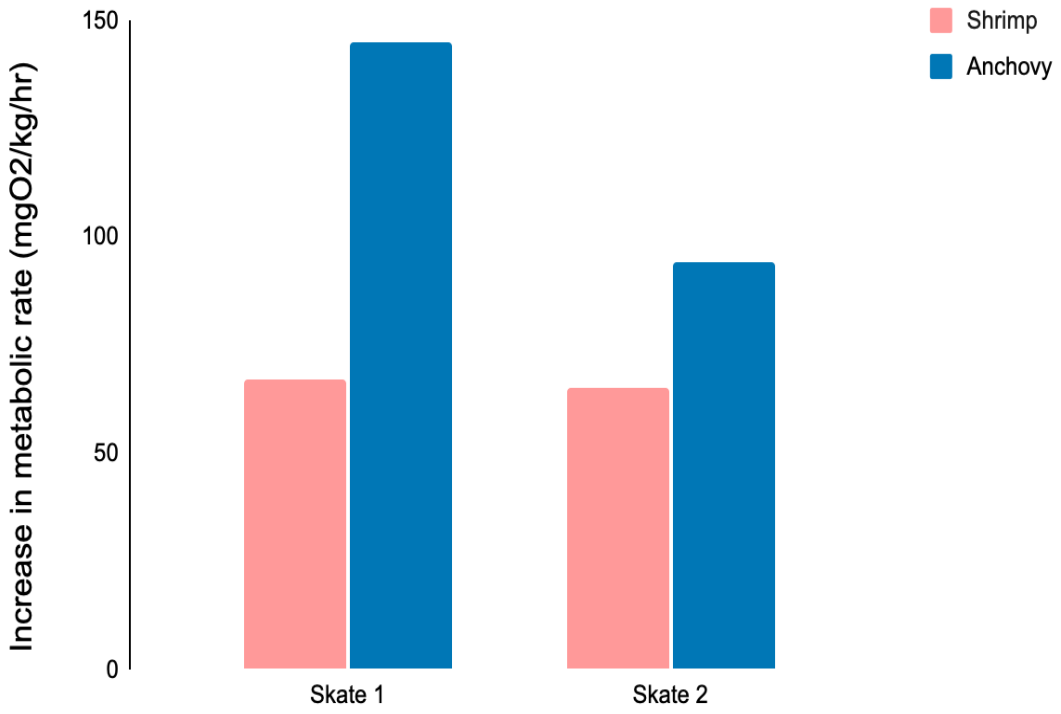

Figure 2 Increase in metabolic rate of the two skates after being fed anchovy and shrimp. These values are the peak MO_2–fasted MO_2 for each trial.

Table 1 Pre-feeding metabolic rates, peak post-feeding metabolic rates, % increase and time of peak associated with the mass of prey eaten for each type.

	Pre-feeding MO_2 ($mgO_2/kg/hr$)	Peak post-feeding MO_2 ($mgO_2/kg/hr$)	% Increase	Time of peak MO_2 (hr)	Mass eaten (g)
	Skate 1				
Shrimp	260	327	26%	0-2	77.87
Anchovy	212	357	68%	2-4	77.55
	Skate 2				
Shrimp	210	275	31%	2-3	81.55
Anchovy	209	303	45%	0-2	37.26

Table 2 Energy expended by SDA (in mgO_2/kg and kJ) versus energy ingested (in kcal and kJ). The ratio of kJ ingested:kJ expended is provided as a quotient.

	mgO_2/kg consumed	kJ expended	kcal ingested	kJ ingested	kJ ingested/ kJ expended
	Skate 1				
Shrimp	283	5.05	66.19	276.94	54.81
Anchovy	786	14.03	101.6	425.09	30.29
	Skate 2				
Shrimp	294.25	6.76	69.32	290.03	42.9
Anchovy	294	6.75	48.81	204.22	30.23

Chapter 4

DISCUSSION

I found that consuming anchovy led to a greater increase in skate's metabolic rate than consuming shrimp, which is contradictory to my hypothesis. Even though it is generally believed that breakdown of protein requires more energy than lipid, it is more likely that the magnitude of SDA is dependent on the combination of a number of components in the diet (Fu et al. 2005). The macronutrient composition of the shrimp *Paneaus raeraturus* from the literature is 24.3% protein and 0.81% total lipid by wet mass (Soriguer et al. 1997). Anchovies are generally lower in protein (12.8–19.8% protein) and higher in lipid content (1.81–15.3% fat by wet mass) compared to shrimp (Boran et al. 2008). These values may slightly differ from the true composition of the prey fed to the skates in the experiment, as composition varies between species and fishing season (Kari et al. 2022). It is possible that anchovies have a higher combined percentage of fat and protein compared to shrimp. The water content of the two prey types may also differ, with anchovies being 65.9–77.9% water (Boran et al. 2008) and shrimp being 75.7–76.9% water (Dayal et al. 2013). While the literature shows that a high-protein diet increases SDA parameters in fishes (Fu et al. 2005), the difference in protein composition in our two diets may not be significant enough, suggesting that other factors are influencing the change in SDA. Further laboratory analysis is certainly needed in order to identify the true composition of the prey used in this experiment.

According to the U.S. Department of Agriculture shrimp and anchovy differ most in their caloric value. 100 grams of raw shrimp is 85 kilocalories, while 100 grams of raw anchovy is 131 kilocalories (fdc.nal.usda.gov). This means that skates are ingesting more energy when they eat anchovies versus when they eat shrimp in equal masses. However, the resulting increase in MO_2 was not proportional to the number of calories consumed between the two prey types in this experiment. The ratio of kJ ingested:kJ expended was greater for both skates after eating shrimp for the first 8 hours of SDA (Table 2). This ratio under the anchovy treatment is consistent for both skates, even when eating different masses (30.29 and 30.23 for Skates 1 and 2 respectively).

This suggests that Clearnose Skates may be feeding more efficiently when eating shrimp instead of anchovy, regardless of the total calories consumed. In this case Clearnose Skates are naturally feeding efficiently, as shrimp compose a larger portion of their natural diet than anchovy (Szczepanski 2013). The species of shrimp and anchovy eaten in this experiment are different from those found in the Clearnose Skate's diet, so the energy gained and lost in a natural scenario may be different from what was observed.

Our values for peak SDA from this experiment are below the range of values from various species in other studies. The maximum increase in MO_2 in this experiment was 68%. Postprandial metabolic rates increased by ~192–235% in Southern Catfish, ~183% in Snakeheads, and 174–223% in Lesser Spotted Dogfish each using similar meal sizes (Fu et al. 2005; Wang et al. 2012; Sims and Davies

1994). In these studies the experimental temperatures were 27.5°C, 25°C and 15°C respectively, while our metabolic rates were obtained at 22 ± 0.5°C. Variations in experimental temperatures may explain the differences in peak metabolic rate, at least for those obtained at higher temperatures because temperature directly impacts metabolic rate. However, our measurements for RMR are much higher than those stated for other elasmobranchs even at similar or greater temperatures (Chen et al. 2008). These discrepancies may be due to differences in experimental design, the design of the respirometry system, or the physiology of the skates. Still, these variables were unchanged throughout the duration of this study, so all trials are comparable to one another.

Since shrimp fed to the skates in this experiment had their exoskeletons removed, there was no effect of chitin on SDA. In a natural scenario this would not be the case. Dietary chitin can decrease the digestibility of protein and lipid in fishes (Karlsen et al. 2015), which could possibly impact the rate or ease of digestion. There are no studies that explicitly investigate the effect of chitin on SDA, so removing the shrimp exoskeleton in this experiment may have had unpredictable effects on our SDA measurements.

Skate 1 ate exactly 6% of her body mass in food for each meal. Skate 2 however, ate only 4.9% and 2.2% of her body mass for shrimp and anchovy respectively (Table 1). This may explain the difference in peak MO_2 and time of peak between the two skates, especially for the anchovy treatment. Meal size also affects SDA in other aquatic ectotherms. Both peak MO_2 and time of peak positively

correlated with meal size in various species of marine crabs (McGaw and Curtis 2013). SDA peak and duration were also correlated with meal size in juvenile Snakeheads (Wang et al. 2012). This can further support the conclusion that digesting anchovy will cause a greater increase in MO_2 than shrimp in Clearnose Skates because Skate 2 ate 44.29 fewer grams of anchovy and had a 14% higher increase in MO_2 (Table 1). Similarly, Skate 2 used a nearly equal amount of energy to digest a smaller mass of anchovy than shrimp in the first 8 hours of SDA (Table 2). Had the meal sizes for each diet been the same, we would expect Skate 2 to use more energy to digest anchovy than shrimp, as was the case for Skate 1.

It is important to capture the entire duration of the SDA effect by allowing the animal's postprandial metabolic rates to return to the same rate as it was when the animal was fasted. Duration and time of peak are variable depending on species just as metabolic rates are variable. In adult Lesser Spotted Dogfish the SDA duration was at least 76.8 hours long with the peak being 6–10 hours after feeding (Sims and Davies 1994). Juvenile Whitespotted Bamboo Sharks had an even longer duration of 122 hours with the peak being at 9 hours (Chen et al. 2008). In this study only Skate 2's postprandial metabolic rates returned to levels similar to that of her pre-feeding rates between 6 and 8 hours after eating anchovy. In the remaining three trials the metabolic rates did not return to the same rate as they were before feeding, so SDA was still in effect for the duration of the measuring period for at least these three out of four trials. Optimally, we would have continued to record metabolic rates after the SDA duration had ended to ensure that the rates stabilized to the pre-feeding level. Having the whole

duration of elevated MO_2 measurements lets us calculate exactly how much energy the animal is using during digestion. This was not possible in this study because the skates were subject to a 12 hour day-night cycle during regular husbandry. Diel changes in light have an unknown effect on skate metabolism, and so comparing metabolic rates with variable light levels could potentially confound the data. For this reason metabolic rates were measured for only 11 hours during the day cycle. Instead of using the entire duration of the SDA effect, we use the amount of energy used in the first 8 hours of SDA to compare the total cost of digestion between trials. Peak SDA is more easily comparable to literature because SDA magnitude usually includes the entire duration of SDA.

The time of peak was somewhat consistent in this experiment, being between 0 and 4 hours after feeding across all trials. While our time of peak is different from what has been observed in other elasmobranchs, time to peak was as low as two hours in both Southern Catfish and juvenile Snakeheads (Fu et al. 2005; Wang et al. 2012). Additionally, time to peak and SDA duration were found to increase with meal size in juvenile Snakeheads, which may explain the early peak and short duration of SDA after Skate 2 ate only 2.2% of her body mass.

Chapter 5

CONCLUSION

We found that Clearnose Skates use more energy when digesting anchovies than when digesting shrimp. This is possibly due to anchovies having a higher combined percentage of lipid and protein in their tissues, but since our estimates of tissue composition are based on literature values, further investigation on the prey species used in this experiment is needed to determine their exact compositions. Clearnose Skates may naturally feed efficiently by having a greater amount of shrimp in their diet than anchovy. It is important that they continue to have viable populations of shrimp to eat, as efficient handling and digestion of food will reserve more energy for their growth, thus increasing their overall fitness. In contrast eating prey which require more energy to digest will cause more frequent feeding in Clearnose Skates. This could be a detriment to populations of prey that require a lot of energy to digest. SDA may occupy a greater portion of a Clearnose Skate's bioenergetic budget when eating anchovy. Clearnose Skates may also experience a greater increase in metabolic rate when eating larger prey, as meal size impacts the duration and peak of SDA. Further research is needed to determine which of the Clearnose Skate's prey provide the most efficient feeding. This experiment can be improved by feeding Clearnose Skates their most naturally frequent prey species, finding the exact macronutrient composition of their prey, and testing more skates for a greater sample size.

REFERENCES

AlFaris, Nora A., et al. “Evaluating the effects of different processing methods on the nutritional composition of shrimp and the antioxidant activity of shrimp powder.” *Saudi Journal of Biological Sciences*, vol. 29, no. 1, Jan. 2022, pp. 640–649, https://doi.org/10.1016/j.sjbs.2021.09.029.

Chabot, D., et al. “The measurement of specific dynamic action in fishes.” *Journal of Fish Biology*, vol. 88, no. 1, Jan. 2016, pp. 152–172, https://doi.org/10.1111/jfb.12836.

Chen, W.-K., et al. “Bioenergetics of juvenile whitespotted bamboo shark *chiloscyllium plagiosum* [anonymous (Bennett)].” *Journal of Fish Biology*, vol. 72, no. 6, Apr. 2008, pp. 1245–1258, https://doi.org/10.1111/j.1095-8649.2008.01766.x.

Dayal, J. Syama. *Shrimps – a Nutritional Perspective*, 10 June 2013.

“Food Composition.” *Food Composition | National Agricultural Library*, www.nal.usda.gov/human-nutrition-and-food-safety/food-composition. Accessed 30 Apr. 2025.

Fu, Shi-Jian, et al. “Effect of dietary composition on specific dynamic action in southern Catfish Silurus meridionalis Chen.” *Aquaculture Research*, vol. 36, no. 14, Oct. 2005, pp. 1384–1390, https://doi.org/10.1111/j.1365-2109.2005.01356.x.

Grayson, Kristine L., et al. “Effects of prey type on specific dynamic action, growth, and mass conversion efficiencies in the Horned Frog, Ceratophrys cranwelli.” *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, vol. 141, no. 3, July 2005, pp. 298–304, https://doi.org/10.1016/j.cbpb.2005.05.052.

Kari, N.M., et al. “Proximate composition, amino acid composition and food product application of Anchovy: A Review.” *Food Research*, vol. 6, no. 4, 3 July 2022, pp. 16–29, https://doi.org/10.26656/fr.2017.6(4).419.

Karlsen, Ørjan, et al. “The effect of dietary chitin on growth and nutrient digestibility in farmed Atlantic cod, Atlantic salmon and Atlantic Halibut.” *Aquaculture Research*, vol. 48, no. 1, 3 Aug. 2015, pp. 123–133, https://doi.org/10.1111/are.12867.

Killen, Shaun, et al. *Guidelines for Reporting Methods to Estimate Metabolic Rates by Aquatic Intermittent-Flow Respirometry*, 19 Feb. 2021, https://doi.org/10.32942/osf.io/gnzh7.

McGaw, Iain J., and Daniel L. Curtis. “Effect of meal size and body size on specific dynamic action and gastric processing in decapod crustaceans.” *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, vol. 166, no. 3, Nov. 2013, pp. 414–425, https://doi.org/10.1016/j.cbpa.2013.07.023.

Sims, D. W., and S. J. Davies. “Does specific dynamic action (SDA) regulate return of appetite in the lesser spotted dogfish, *scyliorhinus caniculcla*?” *Journal of Fish Biology*, vol. 45, no. 2, Aug. 1994, pp. 341–348, https://doi.org/10.1111/j.1095-8649.1994.tb01313.x.

Somonath, B. “Influence of Nutrient Source on Specific Dynamic Action of Pearl Spot, Etroplus Suratensis (Bloch).” *WorldFish*, worldfishcenter.org/publication/influence-nutrient-source-specific-dynamic-action-pearl-spot-etroplus-suratensis-bloch. Accessed 30 Apr. 2025.

Soriguer, Federico, et al. “Lipid, Protein, and Calorie Content of Different Atlantic and Mediterranean Fish, Shellfish, and Molluscs Commonly Eaten in the South of Spain - European Journal of Epidemiology.” *SpringerLink*, Kluwer Academic Publishers, 16 Apr. 2018, link.springer.com/article/10.1023/A:1007327304925.

Sosebee, K. A. 2005. Maturity of Skates in Northeast United States Waters. J. Northw. Atl. Fish. Sci., 35: 141-153. doi:10.2960/J.v35.m499

Szczepanski, John. *Feeding Ecology of Skates and Rays in Delaware and Narragansett Bays*, https://doi.org/10.23860/diss-szczepanski-john-2013.

Tandler, Amos, and F. William Beamish. “Specific dynamic action and diet in largemouth bass, Micropterus salmoides (Lacépède).” *The Journal of Nutrition*, vol. 110, no. 4, Apr. 1980, pp. 750–764, https://doi.org/10.1093/jn/110.4.750.

Wang, Qianqian, et al. “Effect of meal size on the specific dynamic action of the Juvenile Snakehead (channa argus).” *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, vol. 161, no. 4, Apr. 2012, pp. 401–405, https://doi.org/10.1016/j.cbpa.2011.12.015.

Zhao, Shengkai, et al. “Influencing factors of metabolic rates and their implications in thermal comfort research.” *Energy and Buildings*, vol. 339, July 2025, p. 115777, https://doi.org/10.1016/j.enbuild.2025.115777.

Appendix A

TRIAL DATES

Table 3 Trials and dates when each was conducted.

Skate ID; Food type	Date
Skate 1; Shrimp	7/22/2024
Skate 2; Shrimp	7/23/2024
Skate 1; Anchovy	7/29/2024
Skate 2; Anchovy	7/31/2024

Appendix B

RAW DO% VALUES

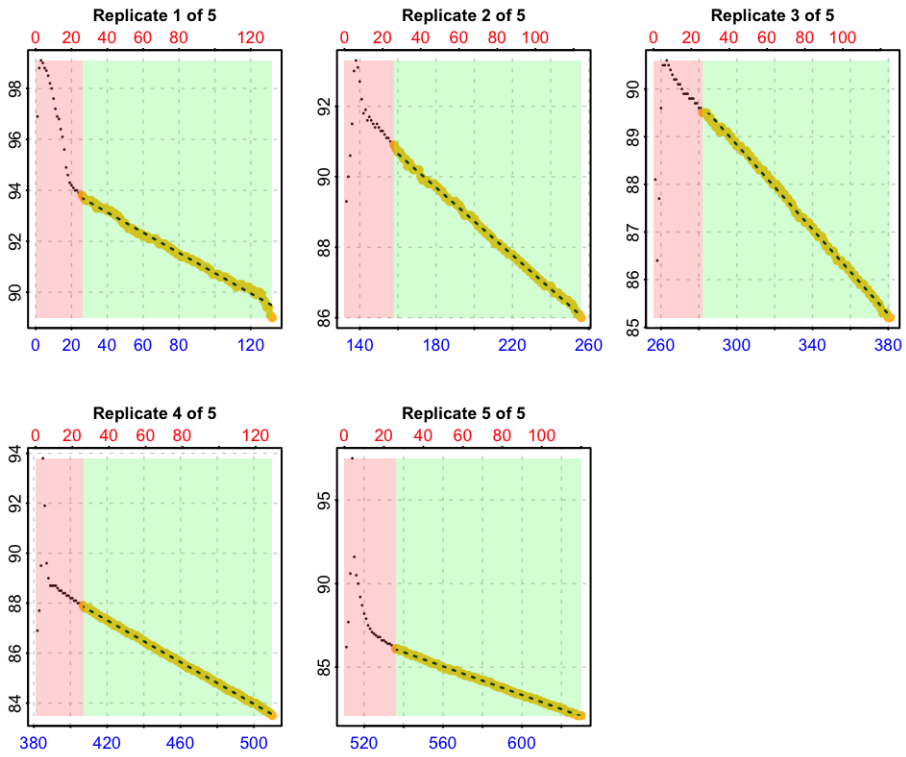

Figure 3 Raw dissolved oxygen % values between each flush for Skate 1's shrimp trial. Replicate 1 of 5 was used to measure fasted RMR. Replicates 2-5 were after feeding. DO% Values in the red shaded area were omitted to exclude elevated DO% measurements from the flush. Values after time=120 in replicate 1 of 5 were excluded from metabolic rate and from standard error because the respirometer was open for feeding. Standard errors for the regression line were 4.922632E-06, 3.190816E-06, 3.044123E-06, 1.788360E-06 and 2.519727E-06 for replicates 1-5 respectively.

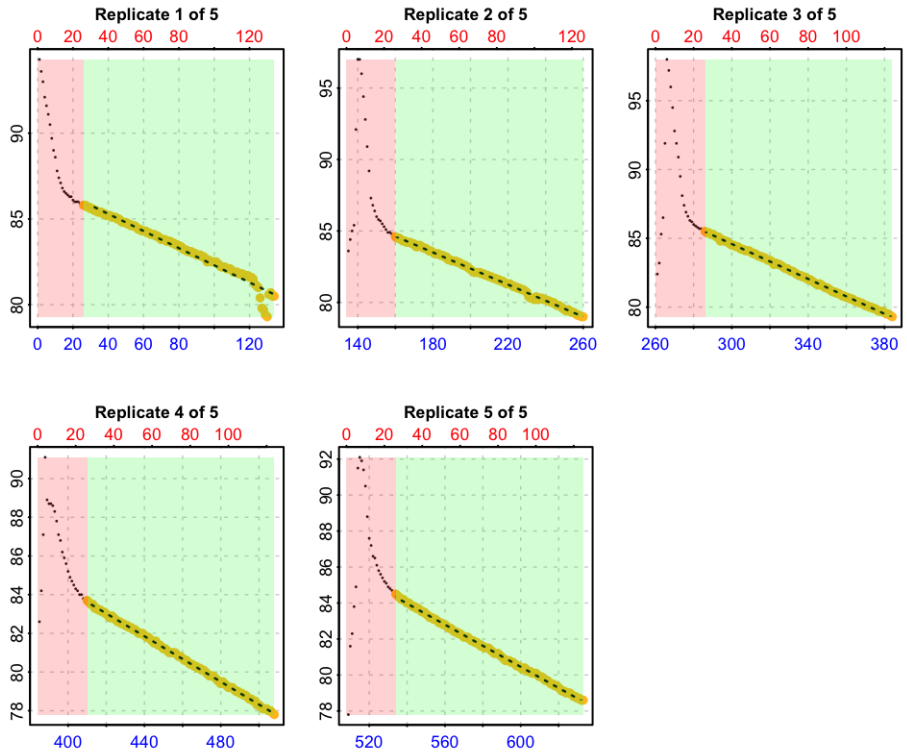

Figure 4 Raw dissolved oxygen % values between each flush for Skate 1's anchovy trial. Replicate 1 of 5 was used to measure fasted RMR. Replicates 2-5 were after feeding. DO% Values in the red shaded area were omitted to exclude elevated DO% measurements from the flush. Values after time=120 in replicate 1 of 5 were excluded from metabolic rate and from standard error because the respirometer was open for feeding. Standard errors for the regression line were 2.831310E-06, 4.454407E-06, 3.502960E-06, 2.793488E-06 and 3.302266E-06 for replicates 1-5 respectively.

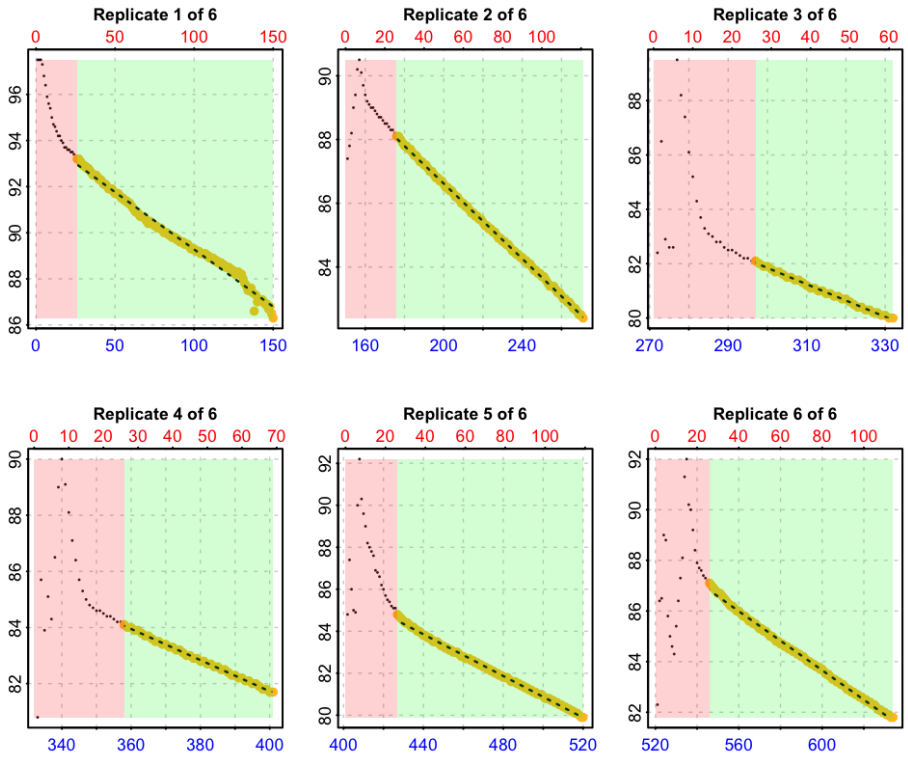

Figure 5 Raw dissolved oxygen % values between each flush for Skate 2's shrimp trial. Replicate 1 of 6 was used to measure fasted RMR. Replicates 2-6 were after feeding. DO% Values in the red shaded area were omitted to exclude elevated DO% measurements from the flush. Values after time=120 in replicate 1 of 6 were excluded from metabolic rate and from standard error because the respirometer was open for feeding. Standard errors for the regression line were 9.422209E-06, 2.859898E-06, 1.077508E-05, 6.632956E-06, 4.333461E-06 and 5.480169E-06 for replicates 1-6 respectively.

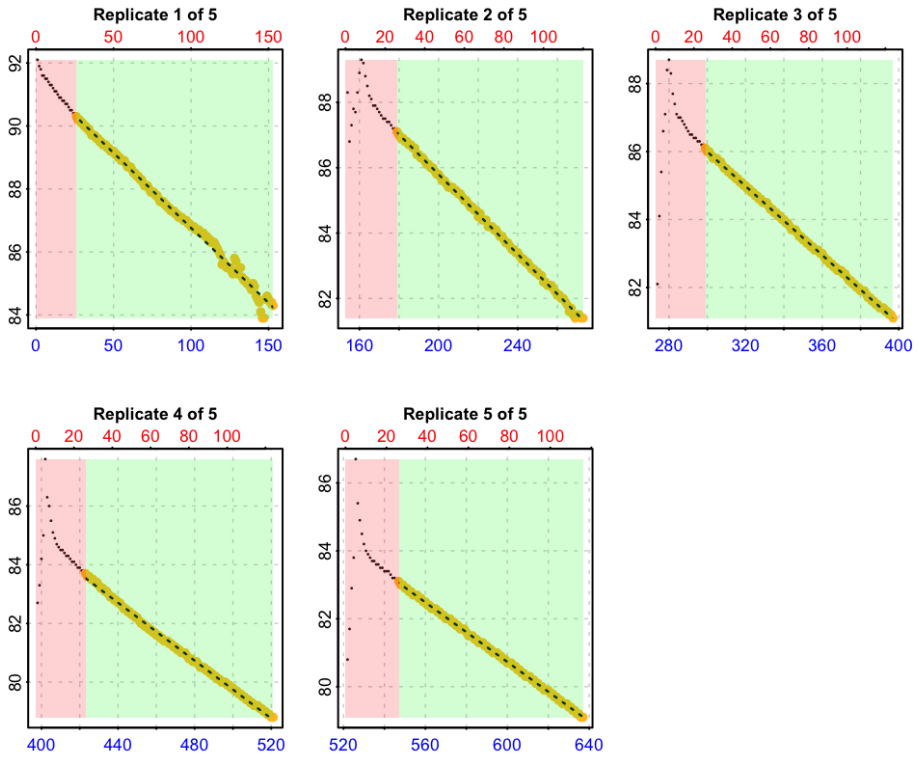

Figure 6 Raw dissolved oxygen % values between each flush for Skate 2's anchovy trial. Replicate 1 of 5 was used to measure fasted RMR. Replicates 2-5 were after feeding. DO% Values in the red shaded area were omitted to exclude elevated DO% measurements from the flush. Values after time=120 in replicate 1 of 5 were excluded from metabolic rate and from standard error because the respirometer was open for feeding. Standard errors for the regression line were 4.598448E-06, 3.234875E-06, 2.088154E-06, 3.976540E-06 and 2.016906E-06 for replicates 1-5 respectively.