

Carbon-14 levels in fish around Ringhals nuclear power plant

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ABSTRACT

^{14}C is a radioactive nuclide which is produced in moderator water in nuclear power plants and small amounts are emitted in both gas and liquid forms. Currently, at Ringhals nuclear power plant (NPP) the liquid emissions of ^{14}C are not being monitored since the methods required are difficult and expensive, and the amount of discharges have so far been considered to be minor. However, increased levels of ^{14}C have been measured, by Lund University, in the marine environment around Ringhals. Previous studies by Lund University have focused on other marine biota, such as bladder wrack while less ^{14}C data have been collected in fish.

One aim of this thesis is to obtain further data on the concentration of ^{14}C in various fish species collected in water around Ringhals NPP, and to compare these data to previously analyzed data in bladder wrack. Samples from 2014-2024 of both yellow eel and corkwing wrasse were received from Ringhals regular environmental program. The results showed that both species of fish continuously had higher levels of ^{14}C compared to bladder wrack.

The second aim of the thesis was to perform a pilot study about possible differences in ^{14}C concentrations across various organs. Differences in concentrations could provide information about the organic chemical forms of dissolved ^{14}C that is released from Ringhals NPP and how they are absorbed by the fish. The liver, stomach, fillet and skin were analyzed from both a European plaice captured close to Ringhals, and a turbot captured in Skagerrak, which was used as a reference. All measurements of ^{14}C were done using accelerator mass spectrometry (AMS).

The reference fish showed no difference in ^{14}C across the organs and it showed generally lower concentrations than the bladder wrack sampled in Särödal that was also used as a reference. The skin, fillet and liver in the European plaice showed no statistical differences in ^{14}C , but were on average 3.7% higher than the levels measured in the turbot (excluding the stomach sample of the European plaice). The European plaice showed increased levels in the stomach, which contained a recently ingested fish. To draw any conclusions about the chemical speciations of organic carbon, and how it is absorbed by fish, more fish samples need to be measured. When including the stomach sample of the European plaice, the levels of ^{14}C were on average 10% higher in the European plaice.

POPULAR SCIENCE ABSTRACT

Har du någonsin undrat hur du blir påverkad av strålning? Du kanske har funderat kring hur kärnkraftverk hanterar utsläpp och hur det mäts och kontrolleras? Alla människor blir hela tiden exponerade för strålning från naturliga källor. Vi påverkas av kosmisk strålning från rymden, strålning av radionuklider som sönderfaller i jordens skorpa, radon i hus och genom maten.

I Sverige säkerställer Strålsäkerhetsmyndigheten (SSM) att allmänheten inte drabbas av en betydande mängd strålning. Den genomsnittliga mängden strålning människor utsätts för i Sverige är ungefär 2.4 millisievert per år och bara cirka 0.02 millisievert av dessa kommer från industrier, inklusive kärnkraftverk. Det är alltså en mycket liten mängd av strålningen allmänheten får i sig som kommer från kärnkraft. Enligt strålskyddslagar får en individ inte utsättas för mer än totalt 0.1 millisievert från ett specifikt kärnkraftverk under ett år. Det finns också ytterligare regler för att skydda anställda i berörda verksamheter från strålning, vilka är att de inte ska få en effektiv dos högre än 20 millisievert under ett år.

I Ringhals kärnkraftverk är alla reaktorer tryckvattenreaktorer och de använder vatten för att både kyla och moderera fissionsreaktionerna i kärnan. I tryckvattenreaktorer finns flera vattenförlöpp och vattnet i kontakt med härden kallas processvatten. Processvattnet värmer en annan krets av vatten, som förångas och genererar energi i en turbin. Vattnet kondenseras sedan i en kondensator för att pumpas tillbaka och bli förångat igen.

Utsläpp sker från kärnkraftverk i form av både luftutsläpp och vattenutsläpp. Några ämnen med radioaktiva isotoper kvarstår i vattnet, såsom bly kvicksilver och nickel. En radioaktiv isotop vars avfall inte mäts är ^{14}C . SSM har sedan 1 mars 2022 bestämt att utsläpp av ^{14}C ska mätas så länge det är rimligt och möjligt. Dock anser Vattenfall, operatörerna av Ringhals, att dessa mätningar inte är rimliga att utföra.

Studier på ^{14}C nivåer i marin biota har även tidigare genomförts av Lund Universitet. Resultat visade högst nivåer av ^{14}C i skärsnultra av alla marina biota som ingick i studien. Baserat på dessa resultat genomfördes detta projekt med syftet att undersöka nivåer av ^{14}C i fiskar. Resultat i detta projekt understryker trenderna i den tidigare studien, det vill säga att fiskar har högre nivåer av ^{14}C jämfört med sjögräs. Detta projekt hade även ett andra syfte som var att undersöka huruvida fiskar kan ta upp ^{14}C på andra sätt än genom dieten och om detta kol skulle ackumuleras i organ med hög fetthalt. Detta undersöktes genom att analysera olika organ av två fiskar, en fångad utanför Ringhals och en fångad i Skagerrak. Datan visade inga indikationer på högre ^{14}C halt i specifika organ förutom i magsäcken i fisken som fångades utanför Ringhals. Fisken hade precis konsumerat en mindre fisk, vilket kan understryka att fiskar får i sig ^{14}C från dieten.

Denna studien visar inte att fiskarna i Ringhals närområde utsätts för en farlig mängd strålning av ^{14}C , dock behöver även lägre nivåer uppmärksammas då det är av vikt att hänsyn tas till samlad mängd strålning.

PERSONAL ACKNOWLEDGMENTS

I would like to thank Kristina Eriksson Stenström who has been my supervisor, for all the help and support. She has been a great help throughout the entire project with both her expertise and her kindness. Guillaume Pedehonta-Hia has also been a great help. Thank you for showing me how to operate the freeze drier at Malmö hospital and freeze drying some samples, as well as collecting them and bringing them back to Lund. I would also like to thank you for the ability to join a sampling excursion for seaweed, it was very enjoyable and interesting. From Geocentrum I would like to thank Mats Rundgren, Ingemar Hansson and Åsa Wallin for showing me around the AMS laboratory. Thank you for thoroughly explaining the systems and the procedures. Lastly I would like to thank Hans Linderson for taking the time to show the laboratory for dendrochronology which has nothing to do with the work, only because of interest and curiosity.

ACKNOWLEDGMENT OF AI

AI, (Copilot and Chat GPT) has sparsely been used in some parts for refining of language and phrasing in the thesis to ensure understanding. It has also been sparsely used to ensure correct coding and presentation of data.

Abbreviations

AMS	Accelerator mass spectrometry
BWR	Boiling water reactor
DIC	Dissolved inorganic carbon
DOC	Dissolved organic carbon
LWR	Light water reactor
NPP	Nuclear power plant
PIC	Particular inorganic carbon
POC	Particular organic carbon
PWR	Pressurized water reactor
SLU	Swedish University of Agricultural Sciences
SSM	The Swedish Radiation Safety Authority

CONTENTS

1. Introduction	1
2. Background	2
2.1. Nuclear power plants in Sweden	2
2.2. Units for ^{14}C	3
2.3. Reference values of ^{14}C in the environment	4
2.4. ^{14}C produced and released in nuclear power plants	5
2.4.1. ^{14}C levels measured in marine life on the Swedish west coast	6
3. Materials and method	7
3.1. Fish samples from Ringhals regular environmental monitoring program 2014-2024 . . .	7
3.2. Fish samples for ^{14}C analysis of specific organs	9
3.2.1. European plaice	9
3.2.2. Turbot	9
3.3. Dissection	10
3.4. Preparation of samples	10
3.5. SSAMS	11
3.6. ^{14}C analysis	13
4. Results and discussion	13
4.1. Fish sample results from Ringhals regular environmental monitoring program 2014-2024	13
4.2. Dissected fish	16
5. Conclusion	18
6. Outlook and further work	18
A. Appendix A	22
B. Appendix B	23
C. Appendix C	24
D. Appendix D	24
D.1. Dissection of round fish	24
D.2. Dissection of flat fish	24

1. INTRODUCTION

All life on earth is affected by ionizing radiation which exists naturally through sources like cosmic radiation from the sun, as well as radionuclide decaying in the crust of the earth. Nuclear power plants (NPPs), contribute to this by releasing much smaller amounts of radioactive nuclides into the environment and one of the emitted radionuclide is ^{14}C [22]. The airborne emissions of ^{14}C from Ringhals NPP are being monitored, but liquid emissions are currently not [26]. The Swedish Radiation Safety Authority (SSM) have the year 2021 instructed that emissions of ^{14}C should be monitored as far as it is reasonable and possible [37]. Vattenfall, the operator of Ringhals NPP also deems ^{14}C measurements in biota to not be reasonable or possible [26].

^{14}C is the nuclide that contributes most to the collective dose that is received by the public and is therefore important to study [22]. It is further of special interest for dose estimates to the general public to study especially fish since the main way ^{14}C is transferred to humans is via ingestion and not inhalation [22].

The thesis will specifically focus on the levels of ^{14}C that are absorbed by fish residing outside of Ringhals NPP and it is done as a part of project SSM2024-9870, financed by the Swedish Radiation Safety Authority (SSM). Earlier measurements done by Lund University for SSM showed that the highest levels of ^{14}C were in corkwing wrasse (*Symphodus melops*) compared to pacific oyster (*Magallana gigas*), blue mussel (*Mytilus edulis*) and bladder wrack (*Fucus vesiculosus*) [33]. Of special interest for fish is the chemical composition of the carbon. Bladder wrack absorb inorganic ^{14}C in form of dissolved CO_2 or bicarbonate, by photosynthesizing, while fish will absorb carbon through their diet. However, it is proposed that fish also absorb ^{14}C in form of dissolved organic carbon (DOC) directly through ingested water or by other mechanisms such as respiration via their gills [33].

The aim of this thesis to get a first look into specifically fish and to study how the levels of ^{14}C in fish samples compare to the levels of ^{14}C in bladder wrack. To achieve this, sixteen fish samples from the years 2014-2024 from Ringhals regular environmental monitoring program were analyzed. The samples received from Ringhals were pulverized fish fillet of corkwing wrasse (*Symphodus melops*) and yellow eel (*Anguilla anguilla*) that were collected by SLU (Swedish University of Agricultural Sciences). Unpublished data of bladder wrack, also collected and analyzed for project SSM2024-9870, was used for comparison.

The thesis is also intended be a pilot study for the way ^{14}C is absorbed by the fish, and especially if DOC can be absorbed via the gills and accumulate in high fat tissue. This second aim was carried out by analyzing measurements of ^{14}C in four different organs. Whole fish were used for dissection, one European plaice (*Pleuronectes platessa*) captured by SLU outside Ringhals, and one turbot (*Scophthalmus maximus*) captured in Skagerrak which was used as a reference. The liver, stomach, skin and fillet were chosen as samples and the liver is of special interest in possible DOC accumulation because of the higher fat content compared to the other samples chosen [12].

2. BACKGROUND

2.1. NUCLEAR POWER PLANTS IN SWEDEN

In Sweden there are currently six reactors in operation, three in Forsmark, two in Ringhals and one in Oskarshamn [35]. There are multiple types of reactors, however all reactors in Sweden are light water reactors (LWRs) which use light water to moderate the fission neutrons. LWRs are divided into boiling water reactors (BWRs) and pressurized water reactors (PWRs) of which Sweden has both [39].

At Ringhals NPP there are currently four reactors, out of which two are in operation. Reactor *Ringhals 1* (BWR, net effect 881 MWe) was closed the 31/12-2020 and reactor *Ringhals 2* (PWR, net effect 900 MWe) closed down 31/12-2019. The reactors *Ringhals 3* (PWR, net effect 1 081 MWe) and *Ringhals 4* (PWR, net effect 1 134 MWe) are currently in operation [40], [45].

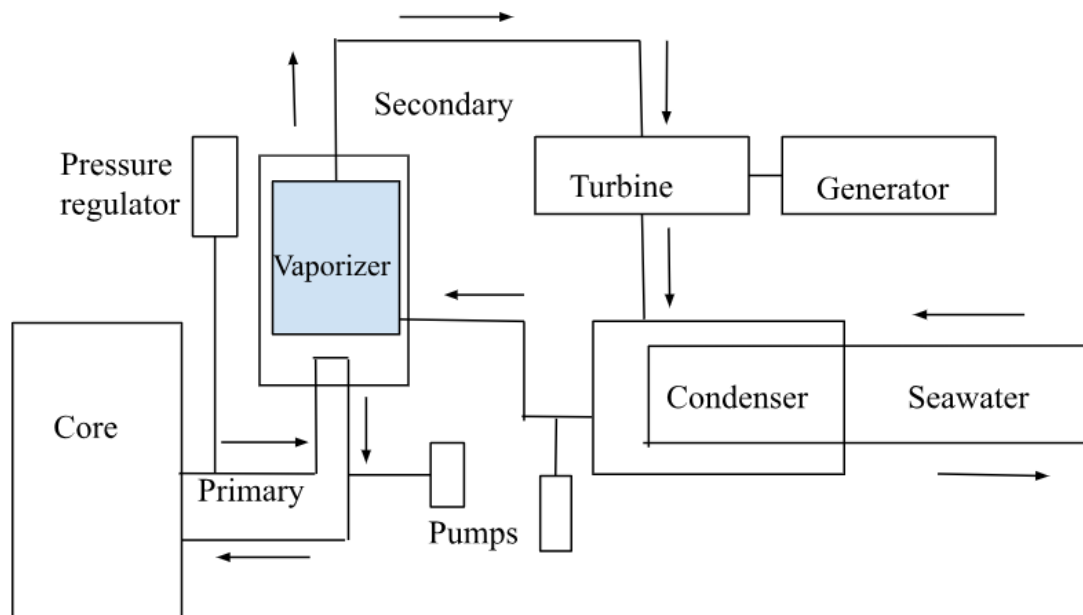


Figure 2.1: Schematic figure showing the separate water flows and sections of a PWR. The primary water flow represents the process water in contact with the fuel, the secondary circuit the water flow driving the turbines, and the seawater the water used to cool down the condenser.

In pressurized water reactors, the moderator water is under high pressure and does not boil even at the temperatures above 300°C. There are three circuits of water, see Figure 2.1, and the circuit denoted as secondary in Figure 2.1), is evaporated and transported via steam generators. The steam is transported to the turbines where electricity is generated. Afterward, the steam is liquidified in the condenser by pipes which have a continuous flow of cooling water that is led into the power plant from the sea. The condensed water is pumped back via the secondary circuit to be evaporated again [42]. The water around the core acting as a moderator for neutrons and coolant for the fuel, is called the process water and is depicted seen in the circuit denoted primary in Figure 2.1. The process water is also reused. The water that is not reused is cleaned and controlled by Ringhals as required by the SSM. If the activity levels are under the regulatory limits the water is released into the sea [38]. IAEA has regulations put in place on how the monitoring is to be performed, which are stated in safety reports [14]. Ringhals NPP releases the waste water continuously, but during revision, which occurs during summer (personal contact with Kristina Stenström, 2026-05-14), the amount of water released could be up to the double. A sample from every tank that is emptied is measured, the results are merged into a monthly sample which is reported in

the NPPs environmental report [19].

Nuclear power plants release small amounts of process water which is to some degree contaminated. At Ringhals NPP the water is sorted based on degree of contamination and is cleaned by filtering, membrane separation with reverse osmosis, ion exchange, evaporation and degassing [43]. A large part of the process water can be reused, and the rest is released through the cooling water outlet [19]. Typical emissions through the process water at Ringhals NPP are small amounts of lead, cadmium, copper, chromium, mercury, nickel and zinc. Moreover, some radioactive nuclide will be released to the water which may accumulate in sediment and marine life. Emissions are measured both in marine biota and water outside of the facility. Samples are frozen in and dried before measured by gamma spectroscopy and tritium emissions in water are measured by liquid scintillation counting [26].

Operation of the reactors in Ringhals cause low amounts of airborne emissions of radionuclides. The air is conducted through a cleaning system which removes parts of the radioactivity, before it is transported outside through the vents. The emissions are considered to have no negative effect on neither the environment close to the facility nor the environment generally [43].

Vattenfall has approximated the resulting effective dose to humans along SSM requirements to not affect humans negatively via ingestion of fish or seafood [43]. The average effective dose of radiation a human in Sweden receives during a year is 2.4 mSv which comes from radon in buildings, medical examinations, food, cosmic radiation and radionuclide present in the crust of the earth [36]. For an individual the effective dose received from the industries working with radiation has to be lower than 1 mSv per year. However, SSM limits the emissions by limiting the maximum allowed dose for people living close to industries such as nuclear power plants. No person living close to nuclear power plants should receive a dose larger than 0.1 mSv per year [38]. A worker in a nuclear facility has an upper dose limit of 20 mSv per year [24].

In Sweden, SSM is the responsible authority for radiation safety and protection of the both environment and the population. SSM considers both immediate and future effects of accumulated radiation doses to avoid unnecessary radiation and unwanted effects [36].

Swedish nuclear facilities including Ringhals NPP abide by the principle ALARA, which stands for as low as reasonably achievable. In practice it means that the protection should be optimized considering social, economic and societal aspects [44]. It is one of the three main principles for protection against radiation which are based on recommendations from the International Commission on Radiological Protection (ICRP). The recommendations are now international standards and incorporated in Swedish law. The second principle is that all radiation should be justified, which means that the benefit of the facility should outweigh the expected harm of radiation. The third principle is that the limits of effective doses should be applied to individuals [13].

2.2. UNITS FOR ^{14}C

To compare ^{14}C values between different materials, isotope fractionation is a crucial effect to consider. Isotope fractionation is the process where certain isotopes are preferred over others in chemical and physical processes [32].

Isotope fractionation for carbon is measured using the quantity $\delta^{13}\text{C}$. It is calculated as follows, using the ratio between ^{13}C and ^{12}C of the sample and a standard material. The value of $\delta^{13}\text{C}$ is different for each material, and is higher for materials with lower depletion of ^{13}C .

$$\delta^{13}\text{C} = \frac{(^{13}\text{C}/^{12}\text{C})_{\text{sample}} - (^{13}\text{C}/^{12}\text{C})_{\text{standard}}}{(^{13}\text{C}/^{12}\text{C})_{\text{standard}}} \cdot 1000\text{‰}$$

For this project all levels of ^{14}C will be expressed in the unit Fraction modern, $F^{14}\text{C}$. Fraction modern is expressed as:

$$F^{14}\text{C} = \frac{A_{\text{SN}}}{A_{\text{ON}}}$$

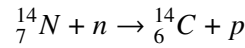
where A_{SN} is the normalized sample specific activity and A_{ON} is the specific activity of a standard. The standard used is OXI, which is the principal radiocarbon standard, NIST oxalic acid. The standard is measured and the value of $\delta^{13}C$ is normalized to -19 per mille [32].

The advantages of using $F^{14}C$ is that the value does not change over time and it is effective when comparing different species since it considers isotope fractionation. Using $F^{14}C$ the specific activity of a sample is calculated as follows [32]:

$$A = F^{14}C \cdot \left(\frac{(1 + \frac{\delta^{13}C}{1000})}{0.975} \right)^2 \cdot e^{(1950-y)/8267} \cdot 226 \text{ Bq/kg C}$$

2.3. REFERENCE VALUES OF ^{14}C IN THE ENVIRONMENT

The radionuclide ^{14}C is a beta emitter with a half-life of 5730 years [23]. Carbon is naturally recycled around earth in a biogeochemical cycle. The levels of ^{14}C in the atmosphere are quite uniformly distributed [23]. ^{14}C is the most important cosmogenic nuclide in terms of public exposure. Cosmogenic nuclide are produced by interactions caused by cosmic radiation and ^{14}C especially is produced by slow neutrons interacting with ^{14}N as seen below [22].



In addition to the naturally produced ^{14}C , the nuclear bomb testing increased the levels significantly. Nuclear bomb testing was conducted between 1945 and 1980 with the most intense periods being between 1952-1958 and 1961-1962 as seen in Figure 2.2. The atmosphere holds an inventory of 140 PBq, from a continuous production of ^{14}C via cosmic radiation. Nuclear bomb testing further increased the inventory by 0.35 EBq. The half-life of the bomb- ^{14}C is approximated to 6 years, because of the quick absorption into the ocean basins. In the year 2008 the remaining bomb- ^{14}C was approximated to be 0.05 Bq/kg in the atmosphere [22].

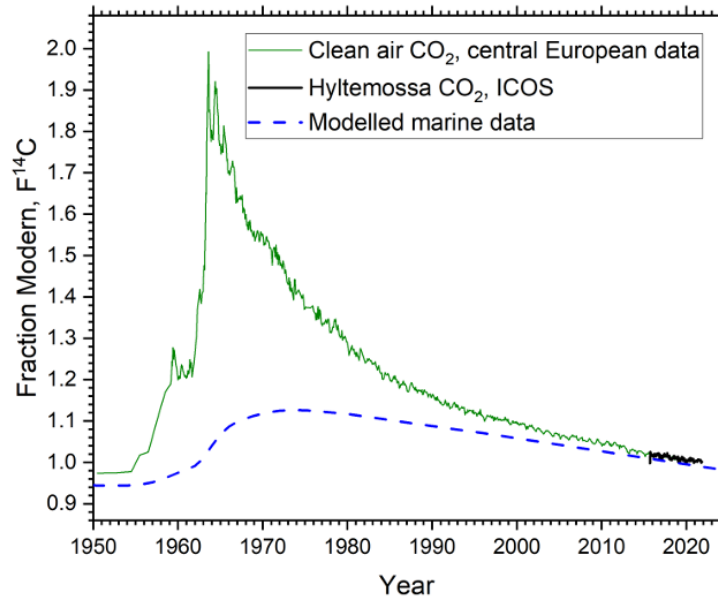


Figure 2.2: The atmospheric and marine bomb-pulse expressed in $F^{14}C$ and its modeled with data collected from the northern hemisphere. Used with permission from Eriksson Stenström et al. [33]

All carbon is part of the carbon cycle and the *exchangable system* consists of the biosphere, atmosphere

and oceans ([2] and references therein). Different phases of the carbon cycle occur at different speed. The exchange of carbon between the surface layers of the ocean and the atmosphere is quite fast whereas the circulation between the surface of the ocean with the deep ocean is slow. The uptake of CO_2 from the bomb- ^{14}C in the oceans is seen in Figure 2.2. The carbon can reside in the deeper parts for thousands of years. The carbon returns to the atmosphere through upwelling of the deep ocean and exchange with the upper ocean layers (see [2] and references therein). The carbon is gradually dispersed into sediment and later on sedimentary rocks where it has a longer residence time.

Carbonic uptake is enhanced in cold and saline waters which give CO_2 levels in water a latitudinal dependence. Carbon is moreover transferred to deeper oceans via the ocean's biological pump. That means the carbon is removed by primary producers such as plankton at the surface, and the carbon is either moved through the food web or down to the deep oceans when the plankton die and sink ([2] and references therein). Organisms that incorporate carbon into their shells as CaCO_3 contribute in a process called the carbonate pump where dissolved organic carbon (DIC) is transferred from the surface to the deeper oceans when they die. Carbon is distributed in several carbon pools and in many different chemical speciations, with the majority in the oceans in form of in DIC [2]. DIC include the chemical forms bicarbonate and carbonate ions (HCO_3^- and CO_3^{2-}), carbonic acid (H_2CO_3) and carbon dioxide dissolved in water. Carbon also exists in shape of particulate inorganic carbon (PIC), DOC and particulate organic carbon (POC). The DOC are organic molecules dissolved in seawater, and POC includes carbon in organic matter such as phytoplankton, zooplankton or dead organisms. PIC represents DIC which as been incorporated in shells by calcifying organisms [33].

2.4. ^{14}C PRODUCED AND RELEASED IN NUCLEAR POWER PLANTS

The emitted ^{14}C is produced both during the operation of the NPPs, but emissions also originate from fuel reprocessing facilities. For operational releases in LWRs, the ^{14}C is produced in the water which moderates the neutrons, also called the process water [15]. ^{14}C is mainly produced by two neutron-induced reactions, both in the fuel and the coolant water as seen in Table 2.1 [15].

Table 2.1: Reactions producing ^{14}C in LWRs [15]

Reaction	Thermal cross section (barns)
$^{14}\text{N} + n \rightarrow ^{14}\text{C} + p$	1.82
$^{17}\text{O} + n \rightarrow ^{14}\text{C} + \alpha$	0.24

The information about specific ^{14}C emissions from individual light water reactors remain scarce, with the exception for airborne releases. The few ^{14}C measurements that actually have been done on process water are from 1980-1990 [47]. Furthermore there is an absence of information regarding chemical speciation of carbon in liquid emissions [47]. Consideration of the chemical speciation of carbon is of importance since seawater naturally contains more carbon in form of DIC. DOC might show larger specific activities in seawater, since the DIC will be more diluted [33].

An estimation of the operational liquid charges has been done to be about 1.3 GBq/a for a 1 GW(e) LWR [15]. The amount of liquid ^{14}C released from NPPs is estimated to be less than 1% of the airborne emissions ([47] and references therein). However, a study by Eriksson Stenström et al. for SSM [33], shows that even though the liquid ^{14}C discharges are smaller than the airborne, the marine biota is more affected.

Tritium (^3H) is another radioisotope that is emitted via waste water and produced in the process water. It is similar to ^{14}C since they both have quite long half lives (12.3 and 5730 years) and reside long enough in both the atmosphere and the hydrosphere in order to be spread globally instead of just affecting the local area around the nuclear power plant [15]. ^3H is as well as ^{14}C easily incorporated into living organisms. Because of these factors, the waste containing them is important to manage [15].

2.4.1. ^{14}C LEVELS MEASURED IN MARINE LIFE ON THE SWEDISH WEST COAST

Around Ringhals, the studies of ^{14}C in marine biota have been issued by Lund University and SSM. A recent study by Eriksson Stenström et al. for SSM [33], studied the marine biota around Ringhals for a year. The study showed that the levels in marine biota were elevated around Ringhals. It showed increased levels in bladder wrack (*Fucus vesiculosus*), blue mussels (*Mytilus edulis*) and corkwing wrasse (*Symphodus melops*). The levels were highest around the cooling outlet (station SLU22, see Figure 3.1), and the highest levels of ^{14}C in organisms were found in corkwing wrasse. Overall, the highest values were measured on biofouling plates. The values measured in study [33] for bladder wrack and corkwing wrasse are depicted in Figure 2.3 and Figure 2.4.

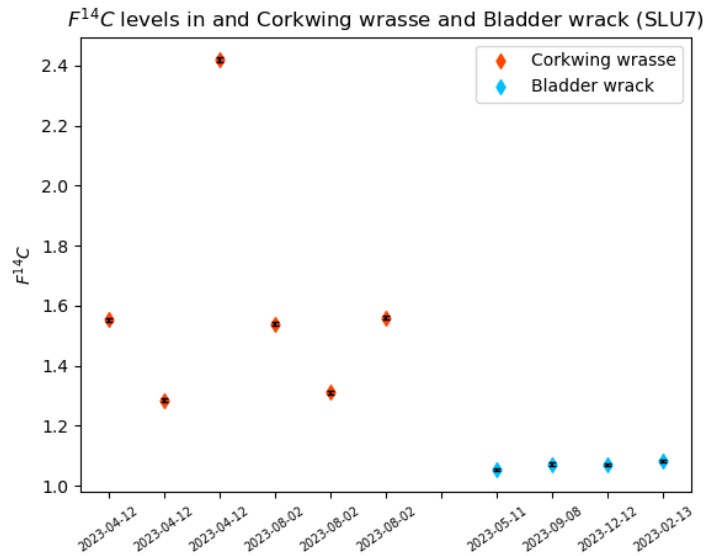


Figure 2.3: $F^{14}\text{C}$ levels in bladder wrack and corkwing wrasse samples from SLU7 found in [33]. The x-axis represents the collection dates of the samples.

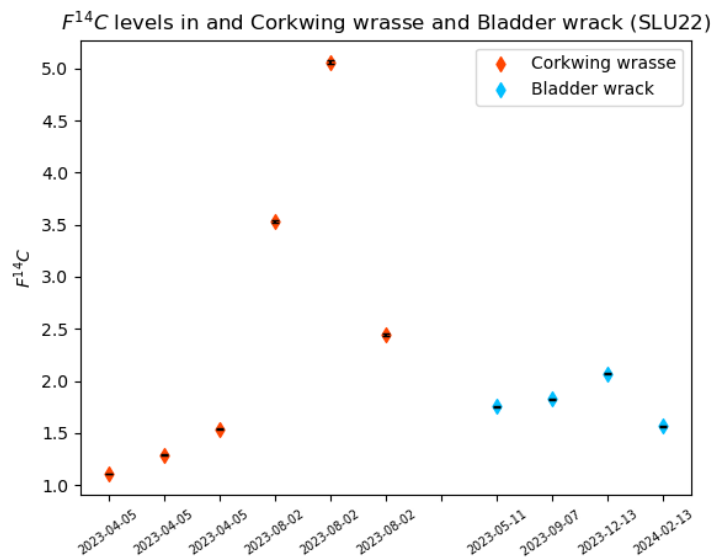


Figure 2.4: $F^{14}\text{C}$ levels in bladder wrack and corkwing wrasse samples from SLU22 found in [33]. The x-axis represents the collection dates of the samples.

Corkwing wrasse exhibit generally higher levels of ^{14}C along with larger differences between individual samples compared to the bladder wrack. The marine biota absorb different chemical speciations of carbon and the absorption occurs in different ways. Bladder wrack absorb only DIC through photosynthesis and fish among other biota absorb ^{14}C via ingestion. As suggested Eriksson Stenström et al suggest in [33], fish can acquire ^{14}C not only by their diet but also small amounts of certain dissolved organic carbon compounds via their gills [9] and some organic compounds accumulate in lipid rich tissue [1]. Moreover, organisms higher up in the food chain might be more exposed to contaminants that have been accumulated and transferred through the food chain which is called biomagnification [1].

Figure 2.5 depicts the marine web for ^{14}C and how it enters and is forwarded in the circular chain for fish, seaweed, crustaceas and mussels [33].

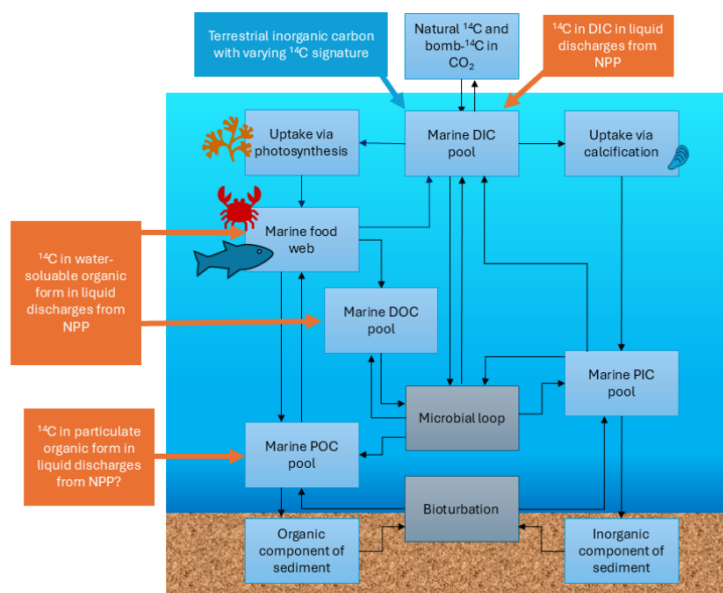


Figure 2.5: ^{14}C transferred from the atmosphere and NPPs into the marine environment, used with permission from Eriksson Stenström et al. [33]

The levels of ^{14}C on the Swedish west coast are furthermore affected by liquid emissions from fuel reprocessing plants La Hague and Sellafield. A study done by Eriksson Stenström et al. [34] on ^{14}C levels in *Fucus spp.* showed correlation with salinity, which indicates that the carbon originates from anthropogenic sources [34]. In the fuel reprocessing facility Sellafield, it has been shown that a major part of the ^{14}C in marine discharges is in the form of CO_2 , CO_3^{2-} , HCO_3^{-} . This is taken up by phytoplankton, and transferred to higher anthropogenic chains and to finally to the sediment when the organisms die. In the water, the levels of organic carbon levels were higher during the summer, and the levels of inorganic carbon higher during winter [7].

3. MATERIALS AND METHOD

3.1. FISH SAMPLES FROM RINGHALS REGULAR ENVIRONMENTAL MONITORING PROGRAM 2014-2024

In the first part of this thesis, samples were received from Ringhals within the project SSM2024-9870. In total 48 fish samples will be analyzed for project SSM2024-9870, but only sixteen are presented in this thesis. The fish samples are compared to already analyzed but unpublished data of bladder wrack, also collected for SSM2024-9870. The samples received from Ringhals were collected between 2014-2024 as seen in Table 3.1 and Table 3.2. Ringhals AB is according to their environmental monitoring program

required to save all samples for ten years [16].

Nine samples of the yellow eel and seven of the corkwing wrasse arrived already dried in plastic containers. Approximately 10 mg (± 1 mg) was retracted from one sample at the time using a small spoon. The sample was placed into a small glass vial on a balance and weighed. To avoid cross contamination the spoon was cleaned with a dry towel between each sampling. After the sample had been added the vials were sealed immediately.

All samples except two samples of corkwing wrasse, were collected at the same sampling site called SLU22, Stalpelskär (N57:15,174, E12:05,479). SLU22 is located 0.2 km north of the release point of liquid waste as seen in Figure 3.1 [17]. As seen in Figure 3.1 SLU22 is located right by the nuclear power plant and the orange arrow points at the water outlet. The remaining two corkwing wrasse samples were collected at sampling site SLU7, Horta (N57:13,497, E12:05,815). SLU7 is located 3,7 km south of the release point as seen in Figure 3.1 [17]. Collection sites, dates and species for all individual samples are presented in Table 3.1 and Table 3.2.

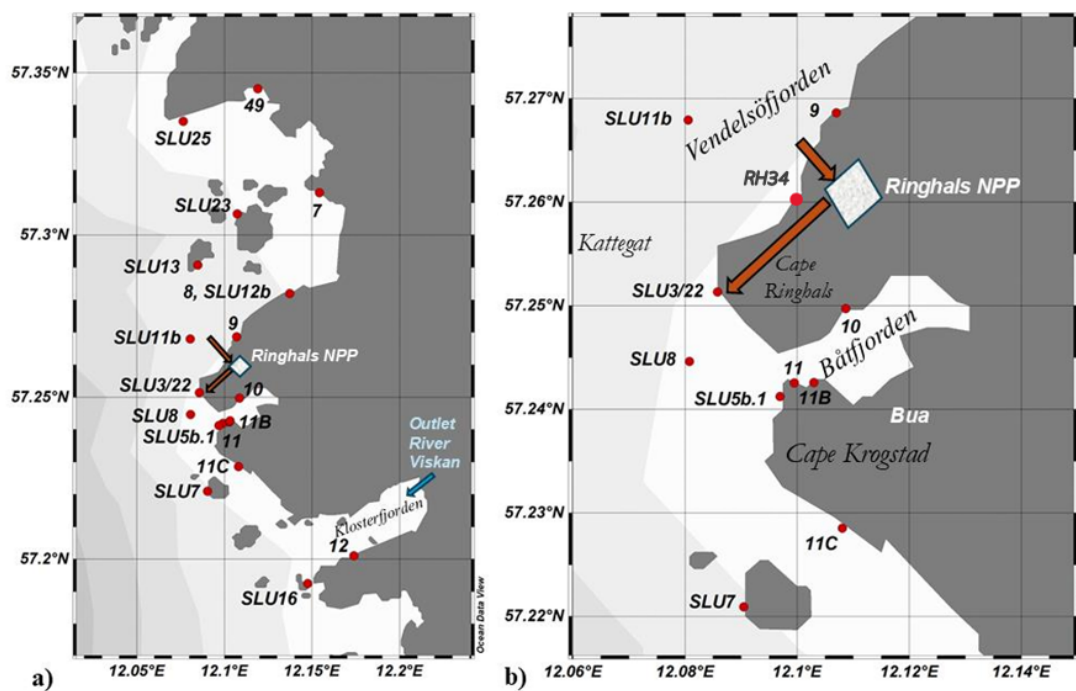


Figure 3.1: A map showing the different sampling points outside Ringhals. From Eriksson Stenström et al [33], with permission.

Table 3.1: The collection sites and dates for the yellow eel samples.

Site	Collection date (YYYY-MM-DD)
SLU22	2014-08-28
SLU22	2015-04-09
SLU22	2016-08-16,19
SLU22	2017-08-08
SLU22	2018-08-01
SLU22	2019-08-01
SLU22	2020-08-04
SLU22	2021-08-01
SLU22	2022-08-09

Table 3.2: The collection sites and dates for the corkwing wrasse samples.

Site	Collection date (YYYY-MM-DD)
SLU22	2020-09-15
SLU22	2021-08-26
SLU22	2022-09-02
SLU22	2023-03-28
SLU22	2024-08-07
SLU7	2023-04-25
SLU7	2023-04-25

3.2. FISH SAMPLES FOR ^{14}C ANALYSIS OF SPECIFIC ORGANS

The lesser sandeel (*Ammodytes tobianus*) and European plaice (*Pleuronectes platessa*) were captured by SLU during week 12 (2026) and brought to Lund in week 13 (2026) for dissection. Both were frozen down by SLU after capture. The fish were captured at station RH34, (N:57.26258, E:12.10395) as seen in Table 3.3. This is located at the intake duct of cooling water for Ringhals 3 and 4. The initial plan of the study was to receive fish captured in the area outside of Ringhals NPP at the beginning of March. However, the weather conditions and ice hindered the fishing. When the fishing was done, it was killed using benzocaine, an anesthetic frequently used in research for painless killing of fish. As benzocaine contains carbon, the samples may have been contaminated and were thus not used. Instead SLU captured five more fish that were killed by percussive stunning (one sharp blow to the head). Out of the five fish, three were European plaice and two were lesser sandeel. Table 3.3 also shows two rows marked red and labelled European flounder as the species which were at first believed to be European plaice but are most likely European flounder. All fish were not used in this study but are still included in the list since they were captured for this project. Differentiation between species was hard because of the small size.

Table 3.3: Information about all individual fish caught by SLU for the thesis.

ID	Species	Station	Date of capture	Length (mm)	Wet weight (g)	Salinity (surface)	Temperature (surface)	Method
RÖSP1	European flounder	RH34	2026-03-10	112	13	21,4	5,2	Benzocaine
RÖSP2	European plaice	RH34	2026-03-10	112	12	21,4	5,2	Benzocaine
RÖSP3	European flounder	RH34	2026-03-19	112	13	20,6	5,3	Clubbed
RÖSP4	European plaice	RH34	2026-03-24	130	21	20,1	6,3	Clubbed
TOBI1	Lesser Sandeel	RH34	2026-03-10	133	7	21,4	5,2	Benzocaine
TOBI2	Lesser Sandeel	RH34	2026-03-10	116	4	21,4	5,2	Benzocaine
TOBI3	Lesser Sandeel	RH34	2026-03-19	129	6,58	20,6	5,3	Clubbed
TOBI4	Lesser Sandeel	RH34	2026-03-24	129	6,64	20,1	6,3	Clubbed
RÖSP5	European plaice	RH34	2026-03-24	122	13,81	20,1	6,3	Benzocaine
RÖSP6	European plaice	RH34	2026-03-24	139	25,26	20,1	6,3	Clubbed

For analysis of different organs, the turnover rate needs to be considered. In wild fish, the turnover rate for ^{14}C is hard to predict, because of the complexity of their food chain [28]. The turnover rate also depends on the composition of the organs, and in animals fat molecules generally have a slower rate [28]. However, a study of stable isotopes (^{13}C and ^{15}N) in summer flounder, showed the fastest turnover rates for liver (10-20 days), followed by blood (22-42 days) and muscle (49-107 days) [5].

3.2.1. EUROPEAN PLAICE

The European plaice lives in the North Sea and along the Swedish coast in the Skagerrak, the Kattegat, Oresund and the southern parts of the Baltic Sea. The species keeps close to the coast and lives on the seabed at depths varying from 25 centimeters to 50 meters [21]. The younger fish keep to the shallow waters while the adults reside further out. Spawning takes place further out at depths of 30-40 meters and the eggs along with the larvae are planktonic. The European plaice may live up to at least 50 years. Their diet consists of bottom-dwelling animals, such as bivalve mollusks and echinoderms. Some of the European plaice take part in fish spawning migration while others are stationary [21]. Fat contents in European plaice captured around the coast of Norway have been estimated in a study where 448 European plaice were captured. The fillet contained 0,67- 4,2% fat while the liver contained 4,6-27% fat [12]. The study also showed that the fat levels varied across species.

3.2.2. TURBOT

The turbot is also found along the Swedish coast, in the Skagerrak, the Kattegat, Oresund and the Baltic sea all the way up to Åland. The spawning takes place at a depth of 10-70 meters and the older fish reside further out [20]. Seasonal migration happens during spring and fall, and individuals migrate up to 100

kilometers. However, they usually move back (within 30 kilometers) in time for spawning. The length is usually less than 50 centimeters and their diet is mostly fish and crustaceas [20].

3.3. DISSECTION

For the second part of the study, nine fish were dissected in total. Five fish captured by SLU were dissected, alongside two herring, one turbot and one other European plaice. The purpose of this part was to obtain information on how ^{14}C released from the Ringhals NPP in different chemical forms is transferred to fish in the marine ecosystem. Four sample types were selected: the fillet, skin, liver and stomach. To get an understanding of how diet impacts the levels the stomach was chosen. The liver is of interest since it contains fat and the aim is to see whether it stores certain chemical forms of DOC and if it can be detected. The fillet is of interest since it can be compared to samples received in Ringhals regular environmental program.

The two herring were captured close to Ven by Anton Eriksson Stenström (2025-11-08) and have since been stored in a freezer. The turbot and European plaice were both bought at Saluhallen in Lund from *Malmstens fisk och kök*. The turbot was dissected the same day while the European plaice was put into the freezer to be dissected the day after. The turbot was caught in Skagerrak and the European plaice was caught in the central north sea (Personal communication with *Malmstens fisk och kök*, 2nd of March, 2026). All fish caught by SLU is reported in Table 3.3. The fish dissected were TOBI3, TOBI4, RÖSP2, RÖSP3 and RÖSP6. As seen in Table 3.3, RÖSP3 was most likely a European flounder. The samples that were prepared and measured were extracted from RÖSP6 (SLU) and the turbot (*Malmstens fisk och kök*).

The dissections of the round fish were performed by first writing a lab manual. For the lab manual one specific video [41] was used to study both the anatomy, and dissection approach. Pictures from this video were used to ensure that the dissection was done correctly and to easier identify the organs. For the flat fish no manual was written and the previous manual was not applicable either because of the vast difference in anatomy. A video was used to learn about flat fish anatomy and dissection approach [27].

All organs that could be identified were extracted, weighed and prepared. The data of all organs that were extracted and not used for the thesis are found in Appendix A. Detailed descriptions of the dissections as well as pictures of some of the fish during dissection are found in Appendix D.

The material that was used for all dissections were scissors with one blunt side, a small knife, a larger kitchen knife, plastic tweezers, metal tweezers and a cutting board. All fish parts were immediately put into containers that were sealed or into a plastic bag which was thrown away directly after the dissection was done. Before the experiment was started, a risk analysis was written.

3.4. PREPARATION OF SAMPLES

In total eight samples were prepared and sent in for ^{14}C measurement, four from the largest of the European plaice and the turbot. The eight samples were freeze dried at Lund University's research department for medical physics in Malmö Hospital. Figure 3.2 shows the specific drier used. All samples were prepared by freeze drying instead of any other method of drying since this method well preserves the biological properties of the samples, and the tissue is not damaged. The freeze drier creates a vacuum which allows the frozen samples to dry via sublimation [4]. Approximately twelve frozen samples were put onto the metal plates and dried over night (Pedehonta-Hiaa, G., Personal Communication 11th of March, 2026). The water contained in the samples is collected in a condenser underneath the sample holder as ice. When the ice melts it is collected by the cup seen at the bottom in Figure 3.2. The samples were small enough for there to be almost no ice collection which allowed new samples to be inserted immediately the day after (Pedehonta-Hiaa, G., Personal Communication 11th of March, 2026). The liver of the turbot had a prominent amount of fat, and still appeared wet. It was therefore refrozen and freeze dried once again but remained the same.

After freeze drying, the samples were pulverized. Most organs were of a soft tissue and were easy to separate into smaller pieces using the same pair of scissors used for dissection. The skin of the turbot was harder and had to first be cut with a knife into smaller pieces. An attempt was made to pulverize the sample using a mixer. The skin was however too thick. Instead it was cut using sharper scissors inside a fume hood to prevent scattering of the sample.

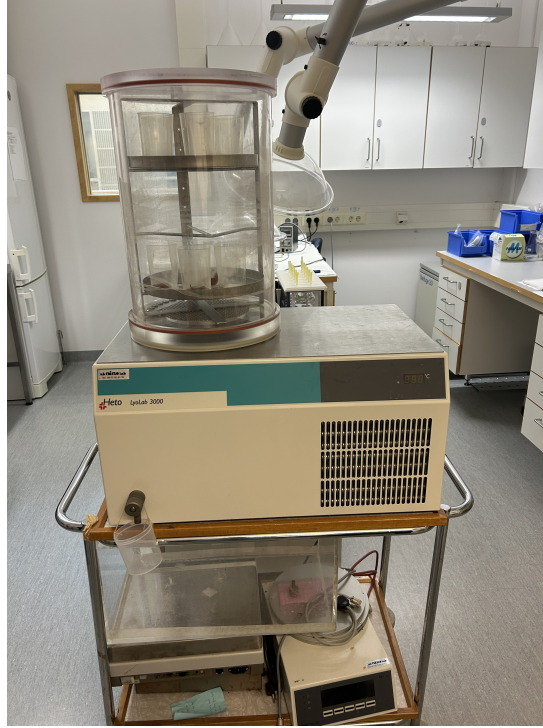


Figure 3.2: Freeze drier at the Medical Radiation Physics department in Malmö hospital.

3.5. SSAMS

Accelerator mass spectrometry (AMS) is a technique that allows counting of single atoms. ^{14}C is the least abundant carbon isotope and has a long half-life, which makes the sensitivity of atom counting instead of decay counting imperative for measurements [11].

Before the measurements can be done, the carbon in the samples is extracted and turned into graphite [11]. At Lund University, the samples are turned into graphite by an automated graphitisation equipment (AGE) [46]. Carbondioxide CO_2 is reduced from the samples by combustion in the elemental analyzer (EA). The samples are wrapped in tin foil and put into the combustion columns in the EA. The sample is burned in oxygen and helium which acts as a carrier gas for oxygen. Excess oxygen is removed in a reduction column, and the rest of the gases, CO_2 , H_2O and N_2 are led through a 4-port valve which leads CO_2 to a zeolite trap and the others to waste. The CO_2 is led into the reactors containing iron powder, by expansion from heating the zeolite trap to 450 degrees. The trap is cleaned with helium flushing in between loading of the samples. To produce graphite, hydrogen is added to the reactors and ovens that can be preheated up to 700° Celcius are lifted to the reactors [46]. The graphite is pressed into pellets which are inserted into one of the ion sources of the AMS machine.

Lund uses a type of AMS called single stage accelerator mass spectrometry (SSAMS) [30]. Figure 3.3 depicts the different parts of the SSAMS machine at Lund university. The parts labelled (1) are ion sources and the part marked (2) is the electrostatic analyser (ESA) [30]. Each ion source, maintained under vacuum, contains a sample wheel with a capacity of 40 graphite samples [30]. The contribution of backgrounds need to be considered and subtracted. Backgrounds refer to ions which are detected as the isotope intended for measure. To subtract these, blanks, which do not contain the isotope intended for

measure, are also prepared and measured [11]. In the sample wheel, four standards are also included, to which normalization is made, and in Lund the primary standard is OXII [29]. Negative ions are accelerated to the ESA and the currents of $^{13}\text{C}^-$ and $^{12}\text{C}^-$ are measured by faraday cups placed after the dipole magnet (3). The ESA is rotatable which is beneficial since it makes switching between ion sources easy and fast. It furthermore improves the energy resolution and narrows the energy range [30]. The dipole magnet remains at constant magnetic field and will deflect the isotopes at different radii as seen below:

$$\rho_B = \frac{\sqrt{2mE}}{qeB}$$

ρ_B represents the radius of the circular trajectory, B the uniform magnetic field, E the energy of the particle, q the charge, m the mass of the particle and e the electron charge [11].

The electric field in the ion source is changed multiple times a second and thus all isotopes are continuously measured. For especially ^{14}C , it is favorable to have negative ions since it excludes interferences with the isobar ^{14}N [10]. The beam is then focused by an Einzel lens, seen as point (4) in Figure 3.3. The beam is led through the acceleration tube of 250kV and further to the Argon stripper gas, (5) and (6) in Figure 3.3 [10]. The stripper gas further excludes isobars of ^{14}C such as $^{12}\text{CH}_2$ and ^{13}CH by breaking them up, since they would have been detected as ^{14}C [10]. Point (8) depicts another dipole magnet, which allows analysis of the different isotopes through mass spectrometry, by sorting away the molecules that were broken up in the stripper gas. The different isotopes are similarly deflected at different radii by the magnetic field [11].

The ^{12}C and ^{13}C are momentum analyzed and measured in two faraday cups placed after the magnet [30]. The $^{14}\text{C}^+$ is energy analyzed by the ESA and the quantity is measured by a surface barrier detector which measures counts of $^{14}\text{C}^+$. In front of the detector, the sequential post-accelerator deflector (SPAD) is located. It consists of two parallel plates and it directs the ^{14}C beam onto the detector and deflects scattered ions. The SPAD lowers background interferences with a factor of two and extends the lifetime of the detector.

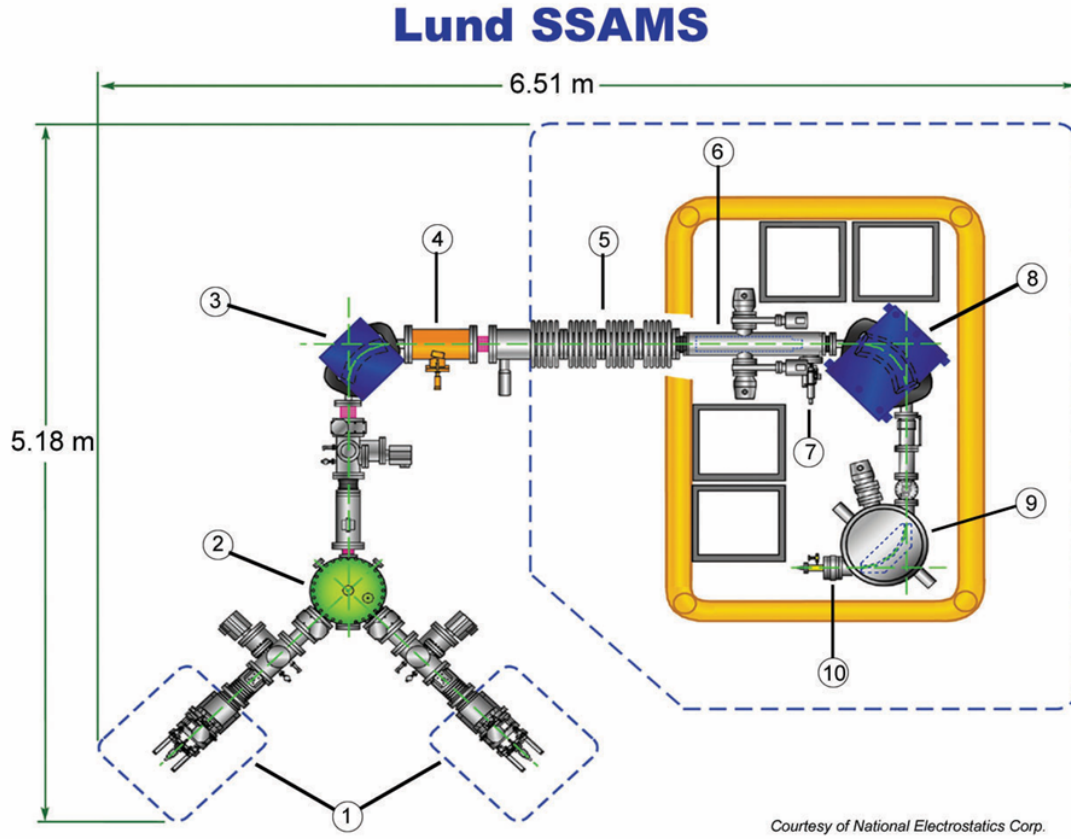


Figure 3.3: The SSAMS machine being used at Lund university. The figure highlights ten parts. 1) Two ion sources containing the sample wheels. 2) ESA. 3) Dipole magnet. 4) Einzel lens. 5) 250kV acceleration tube. 6) Argon gas stripper. 7) Argon valve. 8) Dipole magnet. 9) ESA. 10) SPAD. The picture is courtesy of National Electrostatics Corp. and is used with permission.

3.6. ^{14}C ANALYSIS

The levels of ^{14}C in all samples were measured in Lund Radiocarbon Dating Laboratory's SSAMS machine [30]. The samples were handed in with the required paperwork. The results are given in the unit fM which is the same as $F^{14}\text{C}$ as follows[32]:

$$fM = \frac{A_{SN}}{A_{ON}} = F^{14}\text{C} \quad (3.1)$$

For all fish samples handed in no pretreatment was done before they were turned into graphite.

4. RESULTS AND DISCUSSION

4.1. FISH SAMPLE RESULTS FROM RINGHALS REGULAR ENVIRONMENTAL MONITORING PROGRAM 2014-2024

All data has been plotted using Python and the uncertainties are solely those from the measurements done by the SSAMS machine.

Figure 4.1 shows the measured $F^{14}\text{C}$ in fish samples (yellow eel and corkwing wrasse) from the Ringhals environmental monitoring programme for the years 2014–2024 (sampling stations SLU22 and SLU7). The figure also shows unpublished $F^{14}\text{C}$ data for bladder wrack from the same sampling stations, also collected

within project SSM2024-9870. The data was provided by Kristina Eriksson Stenström. Reference values from Särðal (56.76N, 12.63E) are also included in Figure 4.1.

The Särðal samples are of toothed wrack, (*Fucus serratus*), spiral wrack (*Fucus spiralis*) and bladder wrack (*Fucus vesiculosus*) which all share the genus *Fucus*. Särðal is located about 75 kilometers south of Ringhals and the sample site is believed to be only marginally affected by the discharges of ^{14}C from Ringhals. The $F^{14}\text{C}$ measured in Särðal are mostly natural and bomb- ^{14}C . However, previous studies have shown that Särðal and the entire Swedish west coast also exhibit small traces of ^{14}C released from the nuclear fuel reprocessing facilities at La Hague and Sellafield [34].

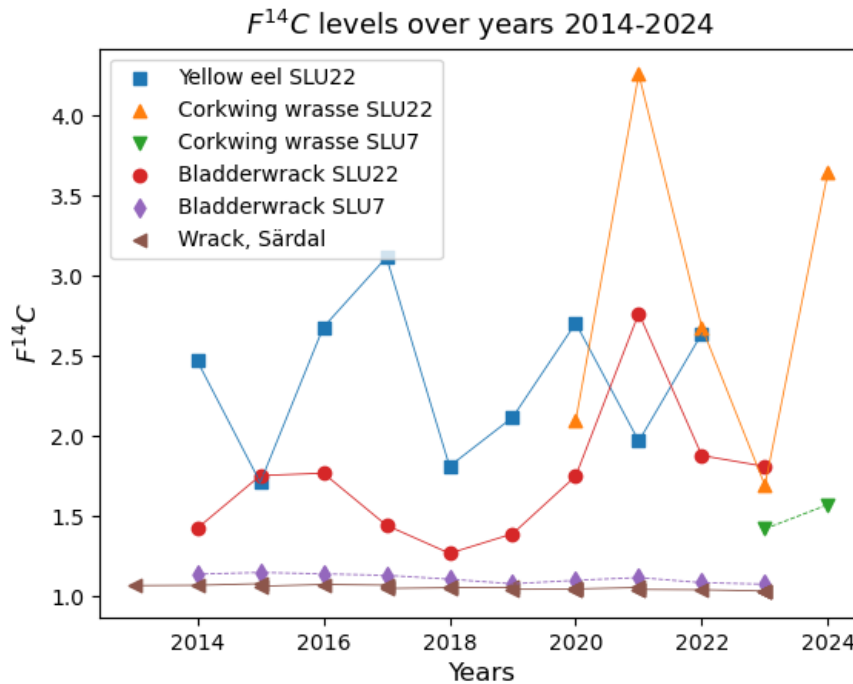


Figure 4.1: The $F^{14}\text{C}$ content in fish and seaweed collected at sampling stations SLU7 and SLU22 between 2014 and 2024. Uncertainties and data are given in Appendix B.

Both species of fish have a consistently higher value than the bladder wrack, except for two sample values, which corresponds to the trend reported by Eriksson Stenström et al. [33]. In that report the hypothesis proposed as to why the levels are higher in fish is because of the difference in how DIC and DOC affect marine biota. Around Ringhals NPP, fish are according to Figure 4.1 more affected by the ^{14}C than seaweed. However, the fillet sample of the turbot showed a value of 0.99 ± 0.004 (see Appendix C) while all Särðal samples show levels of $F^{14}\text{C} > 1$. One reason for this could be the impact of La Hague and Sellafield [34]. Särðal is located on the Swedish west coast and no further specification than "Skagerrak" was given on where the turbot was captured. It could thus have been captured further out and closer to Norway which would mean it was differently affected by Sellafield and La Hague compared to if it would have been close to the Swedish west coast. Moreover, turbot migrate up to 100 kilometers during seasonal migration and adult turbot reside at deeper waters, [20] while the bladder wrack was collected at shore. As mentioned in subsection 2.3, carbon at larger depths is affected by changes much slower than surface water. This means that the ^{14}C is older, and thus the levels of ^{14}C can be lower [18].

It is impossible to know previous residences and for what amount of time the fish has stayed at the sampling site before being captured. This results in larger differences in measurement values among fish samples which have been captured at the same stations during the same years, as represented in [33].

Figure 4.2 depicts the connection between the total annually discharged ^3H from Ringhals NPP measured in waste water (from Ringhals emission reports [25]) and ^{14}C measured in yellow eel and bladder wrack

(from SLU22). Both ^{14}C and ^3H show a spike around 2016-2017 (± 1 year), a dip for 2018 and another spike around 2020-2021. For the yellow eel and bladder wrack, the same data is used as in Figure 4.1. The statistical relation between them is given in Figure 4.3 and the value for p suggests the relation is not statistically significant while the value for r deems the relation to be moderately linearly strong. Most data points are scattered around which makes linear fitting hard, but the fitting still suggests some relation. Moreover, the relation between them is clear in Figure 4.2 which would be expected since both are produced in the process water. Approximations of ^{14}C measurements could thus be strengthened by measurements of ^3H . However, it needs to be considered that the tritium values represent emissions for a full year, while the ^{14}C values represent the total amount of ^{14}C absorbed and processed in fish. As seen in [31], the turnover rate in specific organs (though, for stable isotopes) are between 10 and 107 days depending on the organ). Thus the ^{14}C levels measured in biota do not represent the levels of ^{14}C emitted during the latest year.

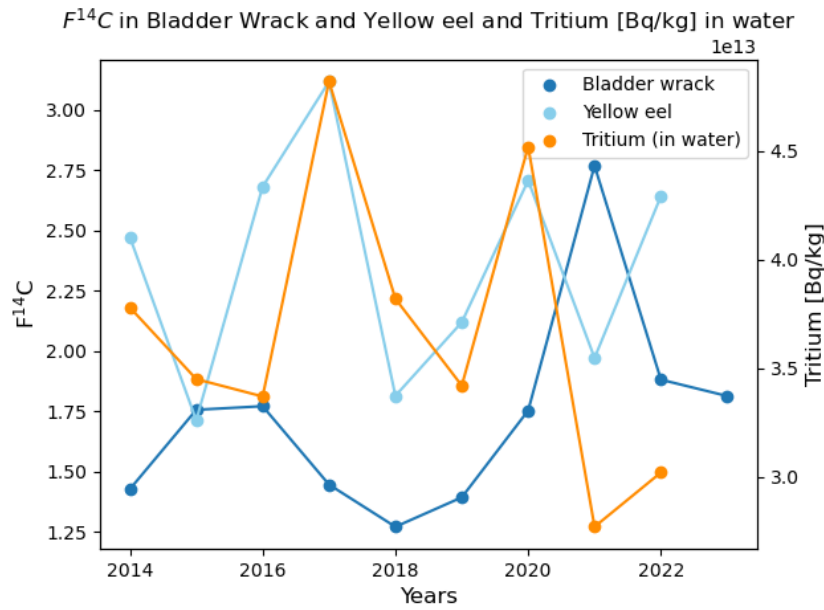


Figure 4.2: $F^{14}\text{C}$ levels in bladder wrack and yellow eel plotted with the tritium levels [Bq/kg] measured in the total waste water during a year from all reactors.

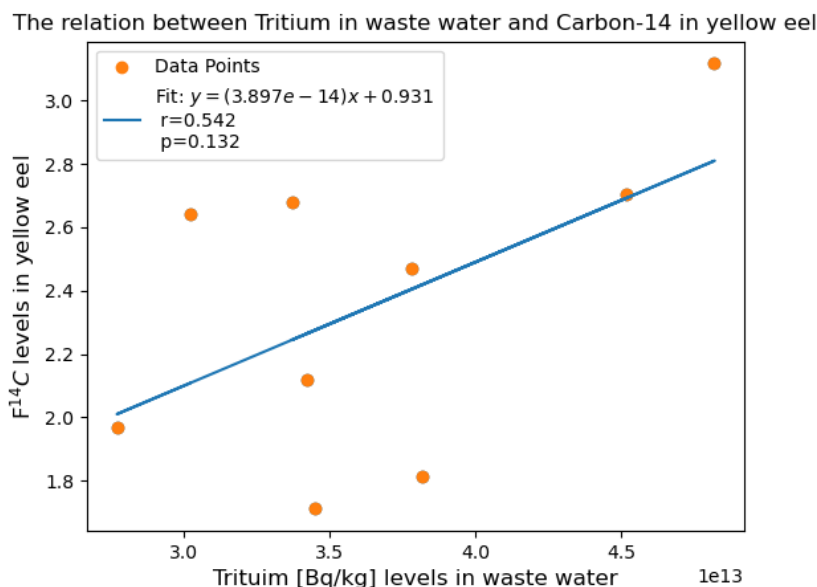


Figure 4.3: The relation between tritium levels in waste water per year, and ^{14}C levels in yellow eel. The linear fit gives $r=0.542$ and $p=0.132$.

4.2. DISSECTED FISH

Figure 4.4 and Figure 4.5 clearly show that the European plaice caught near Ringhals NPP has a consistently higher level of F^{14}C than the turbot caught in Skagerrak. It is clear the fish residing close to Ringhals are influenced by the liquid emissions of ^{14}C . The levels of F^{14}C in European plaice are on average 3.7% higher than those in the turbot, if excluding the stomach sample of the European plaice. When including the stomach sample, the levels are on average 10% higher in the European plaice.

The stomach of the European plaice is a clear outlier as seen in Figure 4.4. Figure D.2 shows the specific fish that was prepared and used for measurements and as can be seen the fish has recently consumed a smaller, long and slim fish. The smaller fish was entirely intact and must have been consumed by the European plaice just before capture. During dissection of the turbot, all content in the stomach was soft and thus at least partly digested. Clearly, the high F^{14}C level in the stomach of the European plaice stem from the undigested fish. Since it was not yet digested, the carbon could not have been transported further to other parts of the fish. The stomach sample consisted mostly of the smaller fish, and less of the actual stomach tissue of the European plaice. The results indicate a higher level of ^{14}C in the smaller fish compared to the European plaice, since the stomach measurement shows higher levels than both the fillet and skin. This could suggest that the smaller fish has before resided in areas closer to the water outlet. Fish residing further out can thus also be exposed to ^{14}C by consumption of fish that have previously stayed closer to the water outlet. The large habitats of fish exposes them to ^{14}C in an entirely different way than stationary biota, such as bladder wrack.

The data of the remaining organs do not suggest higher levels of F^{14}C in any specific organ. For the turbot, the reference fish, the values including the uncertainties overlap. This means that they could statistically be the same. The results show only that there are increased levels in the stomach of the European plaice, which can solely confirm that the diet is a source of ^{14}C for fish. No conclusions can be made about other pathways of ^{14}C than the diet and no evidence was found pointing to DOC accumulation in organs rich in lipids such as the liver.

The age of the analyzed fish might also potentially have influenced the results. The European plaice used was 139 mm in length. Age approximation for fish is usually done using the otoliths, but it can also be approximated from the length. The European plaice are mature at three or five years and they are then

usually between 150-350 mm but the growth is highly dependent on the living conditions [3]. Thus, the 139 mm European plaice would most likely be between a bit younger than three and up to a little less than five years. The turbot was most likely fully grown, and the difference in age might play a roll in how the carbon is absorbed and to what degree it affects the fish. However, for this study it was not possible to have two fish of the same age.

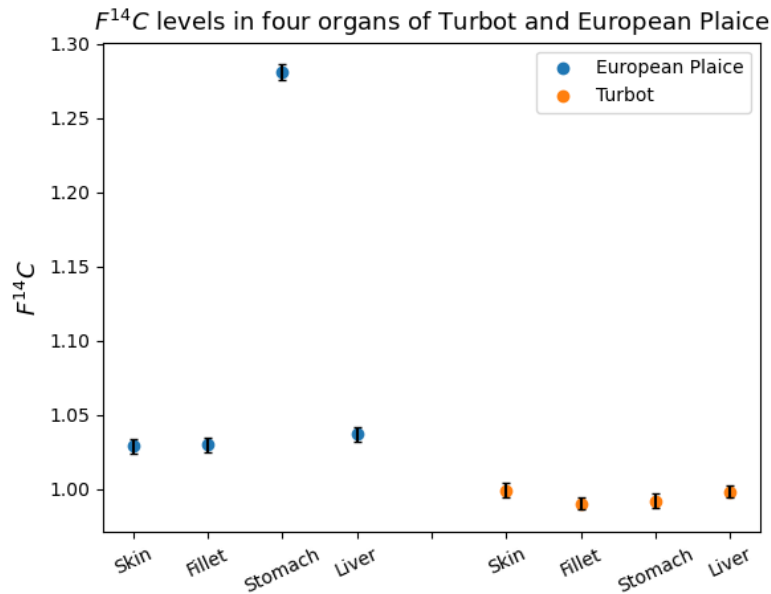


Figure 4.4: F¹⁴C levels in the skin, fillet, stomach and liver of European plaice caught close to Ringhals NPP, and of turbot caught in Skagerrak. Data and uncertainties are given in Appendix C.

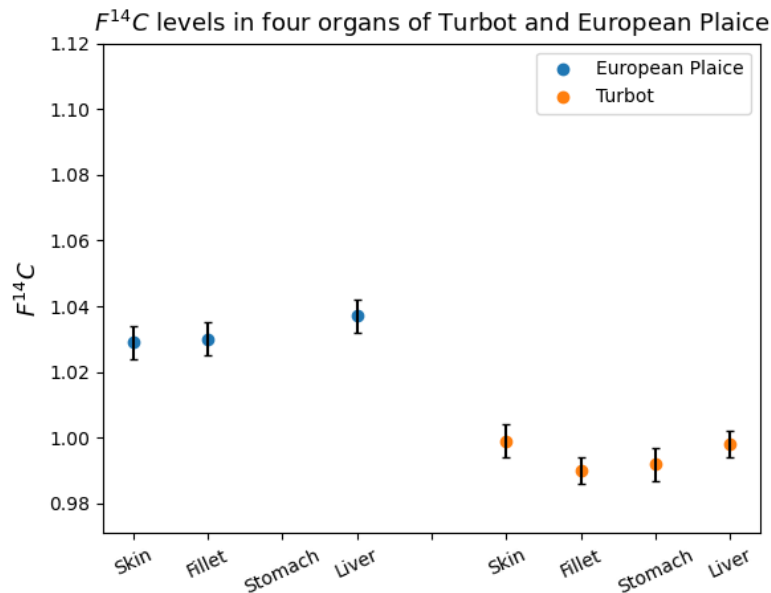


Figure 4.5: F¹⁴C levels in the skin, fillet, stomach and liver of European plaice and turbot. The outlier is cut out to get a clearer view of the other data. Data and uncertainties are given in Appendix C.

5. CONCLUSION

The ^{14}C results for fish and seaweed from the Ringhals environmental monitoring programme (2014–2024) demonstrate that ^{14}C concentrations are regularly higher in fish than in seaweed. No conclusions can be drawn about specific organs containing increased levels of ^{14}C . For this more samples of the same organs would be required from more and preferably older individuals. It would also be preferable if the fish were of the same species for analysis of organs, since the fat content in livers vary across species and even between individuals. What can be concluded from the values measured in the stomach of the European plaice, is that a definite source of ^{14}C is the diet. Possibly the fish might also take up DOC from water that has entered the stomach alongside the diet. This could potentially explain the differences in ^{14}C values measured in fish and seaweed.

More organs would need to be prepared and measured to see where ^{14}C accumulates, and specifically organs with high fat in order to study the direct uptake of DOC, through gills and ingestion of water.

6. OUTLOOK AND FURTHER WORK

This thesis is a pre-study for ^{14}C uptake in fish and more organs than those used in the study were prepared and saved. First and foremost more samples would need to be considered to see how the DIC and DOC affect the fish, for which the remaining samples seen in Appendix A could be used. From just two fish, no clear conclusions can be drawn, especially since they were of different age and species. To see how the diet affects the fish, more species would be needed for the data as well. It would also be interesting to study more organs of fish, such as the brain. A study on zebra fish and F^{14}C done in a laboratory [8] which found that the highest levels of F^{14}C were in the brains of the fish. Comparison with this study would need to be approached with caution since the environment is different and the levels of ^{14}C were much higher than those the fish around Ringhals are exposed to. Otoliths, fish ear stones, would also be of interest since they are metabolically inert [6]. All ^{14}C once incorporated in the otolith will remain permanently. A record showing the levels of ^{14}C that fish have been to for their entire lives can thus be found in the ear stones. The ear stones are mostly made of CaCO_3 and are prominently used for age dating of fish. It would furthermore be interesting in the aspect of DIC and DOC since they are differently incorporated into the otoliths.

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A. APPENDIX A

Table A.1: The organs, and their separate weight, that were extracted from the turbot. The esophagus refers to the intestines from the throat to the stomach. Intestines refer to the intestine from the pyloric caeca to the anal

Organ	Weight (g)
Liver	8.03600
Gallbladder	0.79618
Heart	1.40890
Pyloric caeca	4.37322
Intestine	15.18392
Esophagus	9.25400
Gonads	5.08960
Otoliths	0.05976
Skin	9.72412
Fillet	8.45907

Table A.2: The organs, and their separate weight, that were extracted from the European plaice

Organ	Weight (g)
Heart	0.24817
Otoliths	0.12042
Skin	3.62251
Fillet	7.76904
Kidney	1.07720

Table A.3: The organs, and their separate (frozen) weight, that were extracted from the first herring

Organ	Weight (g)
Stomach	0.942209
Liver	0.7525
Gallbladder	0.26079
Heart	0.29855
Pyloric caeca	1.12995
Gonads	2.90182
Otoliths	0.01210
Scales	0.16759
Skin	0.2100
Fillet	6.54300

Table A.4: The organs, and their separate weight, that were extracted from the second herring

Organ	Weight (g)
Spleen	0.05915
Stomach	1.5034
Heart	0.28111
Pyloric caeca	1.56752
Gonads	14.66400
Otoliths	0.01797
Scales	0.53355
Skin	0.57342
Fillet	3.55534

Table A.5: The organs, and their separate weight, that were extracted from TOBI3 (2026-03-19)

Organ	Weight (g)
Stomach + intestines	0.04462
Liver	0.00547
Heart	0.00450
Otoliths	0.00153
Skin	0.50537
Fillet	1.10142
Roe	1.29737

Table A.6: The organs, and their separate weight, that were extracted from TOBI4 (2026-03-24)

Organ	Weight (g)
Stomach + intestines	0.06591
Heart	0.00575
Otoliths	0.00655
Skin	0.57342
Fillet	3.55534
Roe	1.18455

Table A.7: The organs, and their separate weight, that were extracted from rösp4 (2026-03-24)

Organ	Weight (g)
Stomach	0.12690
Intestines	0.12452
Liver	0.0200
Otoliths	0.00650
Heart	0.06160
Skin	0.47740
Fillet	1.63800

Table A.8: The organs, and their separate weight, that were extracted from Rös6 (2026-03-24)

Organ	Weight (g)
Stomach	0.68476
Intestines	0.38000
Liver	0.12673
Spleen	0.00736
Heart	0.00300
Otoliths	0.01100
Skin	0.63282
Fillet	1.47000

Table A.9: The organs and their separate weight, that were extracted from the European flounder

Organs	Weight (g)
Stomach + intestines	0.28253
Otoliths	0.0065
Skin	0.21852
Fillet	0.76480

B. APPENDIX B

Table B.1: All information of the samples recieved from Ringhals regular environmental monitoring program (2014-2024) (for project SSM2024-9870) including uncertainties from AMS measurements

Species	Date of capture	Station	LuS-number	F ¹⁴ C	ΔF ¹⁴ C
Yellow eel	2014-08-28	SLU22	21462	2.471	0.009
Yellow eel	2015-04-09	SLU22	21463	1.712	0.006
Yellow eel	2016-08-16,19	SLU22	21464	2.680	0.009
Yellow eel	2017-08-08	SLU22	21465	3.116	0.009
Yellow eel	2018-08-01	SLU22	21466	1.813	0.007
Yellow eel	2019-08-01	SLU22	21467	2.118	0.007
Yellow eel	2020-08-04	SLU22	21468	2.706	0.009
Yellow eel	2021-08-01	SLU22	21469	1.970	0.007
Yellow eel	2022-08-09	SLU22	21470	2.641	0.008
Corkwing wrasse	2020-09-15	SLU22	21471	2.098	0.007
Corkwing wrasse	2021-08-26	SLU22	21472	4.258	0.013
Corkwing wrasse	2022-09-02	SLU22	21473	2.679	0.009
Corkwing wrasse	2023-03-28	SLU22	21474	1.694	0.006
Corkwing wrasse	2024-08-07	SLU22	21475	3.649	0.011
Corkwing wrasse	2023-04-25	SLU7	21476	1.423	0.006
Corkwing wrasse	2024-08-07	SLU7	21477	1.574	0.006

C. APPENDIX C

Table C.1: Data of all measured organs in European Plaice and Turbot, shown in Figure 4.4 and Figure 4.5

Species	Station	LuS-number	organ	F ¹⁴ C	ΔF ¹⁴ C
European Plaice	RH34	21566	Fillet	1.030	0.005
European Plaice	RH34	21567	Liver	1.037	0.005
European Plaice	RH34	21568	Stomach	1.281	0.005
European Plaice	RH34	21569	Skin	1.029	0.005
Turbot	Skagerrak	21570	Fillet	0.990	0.004
Turbot	Skagerrak	21571	Liver	0.998	0.004
Turbot	Skagerrak	21572	Stomach	0.992	0.005
Turbot	Skagerrak	21573	Skin	0.999	0.005

D. APPENDIX D

D.1. DISSECTION OF ROUND FISH

During dissection of the herring the manual was closely followed, and the fish was continuously compared to the pictures in the written lab manual. To expose the abdomen a sharp knife was used to make a cut where the blunt scissors were inserted. Using the scissors a cut was made up until the pectoral fins and up around the abdomen, as seen in Figure D.1 b) where the gonads have also been moved out to expose the intestines. Identification of all organs were harder for the sandeel, as seen in Figure D.1 a) the intestines are small. All organs were moved out of the abdomen for easier identification and upon identification everything was cut off at the esophagus and anal. The organs were separated using the smaller knife and put into separate containers.

The final procedure was to look for the otoliths. A cut was made starting from the eye slanting downward. The otoliths were not visible from this angle, and tweezers were vertically inserted to grab the otoliths. A couple of attempts were required in order to get a hold of the otoliths. All organs were weighed and put into the freezer. For one of the herring, the weighing was done subsequently while the other was weighed after being frozen in.

D.2. DISSECTION OF FLAT FISH

The flat fish was put down with its underside facing downward. In flat fish the organs and anus are located close to the head. Once again the fish was cut from the anal and upward by cautiously making a cut with the sharp knife to easier insert the scissors. With the gut entirely exposed it was clear that the liver had been punctured while cutting. The skin of the turbot was the toughest out of all dissected fish, and therefore extra force had to be taken while cutting, and thus puncturing the liver. The liver was extracted in liquid form by lifting the fish and pouring the liver into a cup. Since the European plaice was very young the skin was soft and easy to cut through and all organs were cleanly extracted.

To identify the separate organs, the stomach and intestinal system was untangled and put outside of the bodies of the fish but still connected via the anus and throat. When the parts had been identified they were cut out as seen in Figure D.2. Regarding dissection of the smaller European plaice, all organs were significantly harder to identify because of the size. The heart lied under the gills behind a protective piece of skin. It was carefully cut up, revealing the heart which was carefully pulled out using tweezers and cut out using the small knife.

At the end of the dissection the otoliths were extracted. The procedure for flat fish differed from that of round fish because of differences in brain anatomy. Initially, two cuts were made which created a



(a) Lesser sandeel

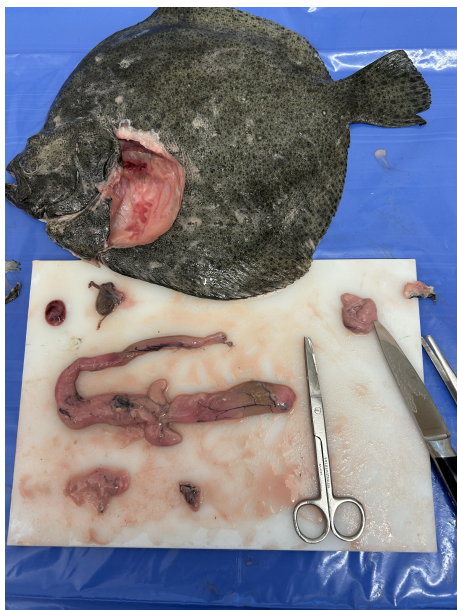


(b) Herring

Figure D.1: A lesser sandeel and a herring with their intestines laid out during dissection.

triangular opening. It quickly became clear that the otoliths were not reachable using tweezers from this angle. Instead an additional cut was made to remove a larger part from the top of the head which revealed the otoliths. In comparison to the round fish, the otoliths of flat fish were bigger and placed against the back of the skull which made them easily removable. For all cutting regarding the otoliths in the turbot, the bigger knife was used because of the thick skull of the turbot.

Finally, fillet and skin samples were collected. The fillet was removed by cutting horizontally along the fish. The skin was peeled off by hand and the remaining fillet attached to the skin was scraped off with the knife.



(a) Turbot



(b) European plaice

Figure D.2: A turbot and a European plaice with their intestines laid out during dissection.