Deliverable D5.1

WP5 Implementation Plan

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About this document

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Work Package	WP 5, Impacts of Fishing and Industrial Extraction processes on the Ocean C cycle
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1. Abstract

Work Package 5 of Ocean ICU is aimed at investigating the effects that large-scale anthropogenic activities exploiting marine resources have on processes of the marine carbon cycle. The anthropogenic activities that will be addressed are (1) mining of mineral resources in the deep-sea, (2) bottom-trawling fisheries and dredging in continental shelf seas, and (3) fishing in off-shelf open seas and (4) fishing in shelf seas. While the first two aspects evolve around the effects of removing the bioactive benthic surface sediments and suspending those into the water column thereby creating plumes with high particle loads, the latter two aspects impact the carbon cycle by removing fish biomass in the water column.

Results of this work package will be communicated to our stakeholders (WP8), and developed scenarios will be fed into the decision support tools in WP7. The connection with WP6 will explore the possible larger-scale effects on the regional and global C cycle.

This document outlines the proposed implementation plan for the work package, stating its main objectives, deliverables and milestones to be achieved by the end of the project as well as its connections with other WPs of OceanICU.

2. Introduction

2.1. General description

WP5 will quantify the impact of resource extraction processes, i.e. deep-sea mining, dredging, drilling and bottom-trawling as well as fisheries, on the contemporary ocean C cycle.

WP5 objectives are:

1. Assess the impacts of seabed mining and drilling on sediment in the water column on C sequestration
2. Evaluate the impacts of bottom trawling and dredging on biogeochemical and biological processes influencing carbon sequestration
3. Determine the scale and impacts of on-and off shelf fishery removals directly on carbon sequestration, and indirectly via food web changes, including relevant impacts on the seabed
4. Provide knowledge, parameterizations and scenario output for habitat models and fishing pressure impacts on carbon sequestration.

The specific tasks of WP5 are:
Task 5.1 Impacts of deep seabed mining and drilling activities on the open ocean (Lead: GEOMAR; Contributors: NIOZ). Drilling and mining activities resuspend sediment discharging waste at a range of depths. We will investigate the effect of depth injection using existing a) biogeochemical and microbial data b) an industrial collector trial to quantify the changes of carbon burial and remineralization processes. We will use the MITgcm model to assess the depth dependent impacts of the redeposition of plume material on carbon sequestration.

Task 5.2 Impacts of sediment generating (e.g. dredging, trawling) activities on the shelf sea ecosystems (Lead: NIOZ; Contributors: PML, GEOMAR, MI). Trawling and dredging are similar in that they cause near bottom resuspension. We will investigate their impact using a coupled biological-biogeochemical sediment model, OMEXDIA to resolve the impact of bottom-trawling fishing gears on the carbon burial and remineralization processes. Combined with maps of fishing intensity, the model will quantify the scale of trawling-induced changes of carbon burial, remineralization and release of porewater into bottom water. The complex NEMO-ERSEM NW European Shelf model will quantify changes on biological pump processes (e.g., enhancing particle export) and CO2 fluxes from bottom-trawling generated sediment plumes.

Task 5.3 Impacts of fishing on carbon sequestration in the on-shelf ecosystem (Lead: MI; Contributors: DTUAqua, English Nature, Agrocampus Rennes, Strathclyde U.) (M06-42) We will investigate the impacts of overfishing on the C cycle using Ecopath with Ecosim (EwE), Ecotroph & StrathE2E and what changes would be expected under different fisheries management scenarios. EwE will focus on the Celtic Sea. StrathE2E will perform a series of case studies from the Arctic Ocean to the S. Atlantic, and Ecotroph will focus on the Atlantic Basin scale.

Task 5.4 Impacts of fishing on carbon sequestration in the off-shelf ecosystem (Lead: DTU-Aqua; Contributors: SPC, MI, DTU-Aqua, English Nature, Agrocampus Rennes, Strathclyde U.) (M06-42). This task will investigate the effect of exploitation of both epi- and mesopelagic fish on the C cycle. It will consider both the direct impact of removals on carbon budget, and the indirect effects through the food web on the wider aspects of biological carbon sequestration. This task will draw on information from ongoing EU projects including MEESO and SUMMER to provide likely biomass predictions and their possible ranges using the FEISTY & SEAPODYM size spectrum models.

Task 5.5 Transfer knowledge to DSTs (Lead: MI; Contributors: DTU, GEOMAR, NIOZ, English Nature, Agrocampus Rennes, Strathclyde U) This task will deliver information around the role of fishing and industrial exploitation to WP7.

2.2. Deliverables and milestones

Table 1: List of deliverables

Number	Title	Lead	Delivery month	Contributions
D5.1	WP Implementation Plan based on discussions at first GA including draft of how to achieve KPI delivery	MI	M16	all
D5.2	Summary of material passed to WP 7 in M5.1 that quantitatively links the intensity of human pressure to C cycle impacts in all four areas (Tasks5.1 - 5.4)	MI	M30	all
D5.3	Summary of material passed to WP7 in M5.2 that reports the final analysis of how fishing and Industrial processes impact the C cycle from WP5.1 to 5.4 transferred to WP7 in M5.2	MI	M42	all
D5.4	Summary of all work within the WP including estimates of how industrial processes control ocean C in the modern ocean with submitted manuscripts	MI	M50	all

Table 2: List of milestones

Milestone No.	**Milestone tiltle**	**Due date (months)**	**Means of Verification**
M5.1, M5.2	Data Transferred from WP5 to WP7	28, 40	Data sets archived

3. WP5 implementation

3.1. Task 5.1: Impacts of deep seabed mining and drilling activities on the open ocean

In Task 5.1 we have identified that impacts of deep-sea mining activities are expected to have larger spatial footprints in the marine environment than other industrial processes, such as dredging and drilling. Since the International Seabed Authority (ISA) is currently drafting the regulation for the exploitation of mineral resources, closing scientific knowledge gaps of impacts from deep-sea mining is also a priority in marine policy. Therefore, we have decided to focus our work on this industrial activity.

For economic reasons companies interested in deep-sea mining expect that they need to harvest 2-3 Mio t dry weight of polymetallic nodules (PMN) per year and mining operation. In economically interesting areas, such as the Clarion-Clipperton Zone (CCZ) in the SE equatorial Pacific, where the ISA has issued 18 exploration contracts until today, this equates to an area of 200-300 km^2 per year and mining operation. Current technology for mining of PMN will remove together with the resource also the entire bioturbated layer of the seafloor sediments, including its epi- and endofauna. The main fraction of the removed sediments is suspended into the bottom water at the back of the vehicle, and disperses driven by its own density-driven hydrodynamics and the bottom currents. An additional sediment plume is created in the water column by the discharge from the surface platform after cleaning of the nodules from remaining sediment. The largest fraction of the suspended sediments will sink to the seafloor, where it will blanket the fauna, thereby impacting an additional area. First data on the resulting impacts on the marine environment and the behaviour of the suspended sediment plume are available from the MiningImpact project, which collected data in connection with the first industrial test of a collector vehicle in the CCZ. Some additional information was produced in connection of benthic impact experiments conducted more than 25 years ago and that have been revisited in the course of the MiningImpact project.

Individual steps to be undertaken:
(1) Months 10-18: Based on the existing data and information we will develop scenarios for industrial scale mining operations to simulate the resulting footprint of impacted seafloor area and affected ocean water volume as well as its evolution over the expected timescale of a mining operation (1/10/30/50 years), expected multiple parallel operations (1/5/20), and different water depths of the return waste discharge (<1000/1500-2000/>4000 m).

(2) Months 18-42: Numerical simulations of the scenarios and analysis of sediment plume dispersal and interaction with C cycle processes in the water-column. In these scenarios both sediment plumes, the one suspended by the collector vehicle and the second generated by the return waste discharge in the water column will be considered. Anticipated impacts in the water column include scavenging of organic and inorganic carbon by particle aggregation leading to enhanced export fluxes to the seafloor and effects on the diel plankton migration. In addition, these sediment plumes may affect fish stocks and fishing activities in the high seas and possibly also coastal areas. In collaboration with WP6 we will then choose appropriate scenarios to investigate regional scale effects on the C cycle.

(3) Month 36-48: Quantification of impacts on benthic carbon fluxes and processes based on results of footprints from sediment plume scenarios. Previous modelling studies and biogeochemical data from benthic impact experiments indicated that removal and disturbance of the bioactive surface sediment layer in the mined area leads to strongly reduced organic carbon remineralization and bioturbation rates. Recovery of these processes may take several thousands of years. In contrast, data from areas with thick (>1 cm) sediment blanketing shows increased oxygen consumption (i.e. increased POC degradation). We will employ the diagenetic model C.CANDI to simulate the data from the first industrial collector tests, and update predictions for recovery of POC remineralization processes applying the defined industrial-scale mining scenarios.

3.2. Task 5.2: Impacts of sediment generating (e.g. dredging, trawling) activities on the shelf sea ecosystems

Shelf-sea sediments harbour significant levels of biodiversity that play a key role in ecosystem functions and services such as biogeochemical cycling, and carbon storage. Bioturbation and bioirrigation, the faunal activity that results in particle displacement and increased exchange of solutes (e.g. CO_2) across the sediment-water interface and within the sediment matrix, has a large impact on the degradation of organic matter into inorganic bioavailable forms and thus on carbon sequestration.

In addition to directly changing the sediment biogeochemistry, bottom disturbing activities also remove benthic organisms and change the species composition. This alters the functional traits in terms of bioturbation and bioirrigation of a community, which in turn may have broad implications for the overall biogeochemical functioning of the sediment.

To include this biological-biogeochemical interaction, our impact assessment couples a biological and biogeochemical model:

In (i) the *biological* part, a data-driven mechanistic model is used to describe species depletion during and recovery between trawling events. As the species densities change due to trawling, so do the bioturbation and bio-irrigation activity performed by the biological community. This has impact on (ii) the *biogeochemical* model, which is an early diagenetic model, based on OMEXDIA. Upon trawling, the sediment and organic matter in this model is mixed and partly resuspended, while porewater with nutrients, and organic carbon is lost to the overlying water column.

First results on the biological part are available, and steps have been taken to couple this to the biogeochemical model.

Individual steps to be undertaken:

Months 18-24: To estimate the impact of bottom fishing on benthic organisms, we take a trait-based approach. We will apply this biological approach to North Sea data sets and test the validity of our model predictions.

Months 18-36: The impact of trawling on the coupled biological - biogeochemical processes will be applied to the North Sea biogeochemistry. Combining biological and biogeochemical data from this area with maps of fishing intensity, the model will quantify the scale of trawling-induced changes of carbon burial, remineralization and release of porewater into bottom water.

Months 24-48. Coupling of the model with the NEMO-ERSEM model is part of WP6. PML will port the relevant elements of the trawling impact model into 3D ERSEM simulations of the NWES and assess the impacts on carbon cycling in representative scenarios.

3.3. Task 5.3: Impacts of fishing on carbon sequestration in the on-shelf ecosystem

Task 5.3 will examine the role of fishing on carbon sequestration in the shelf sea context. This will be carried out using three modelling systems.

The first is StrathE2E (led by Mike Heath at University of Strathclyde, UK). StrathE2E is a marine food web model of intermediate complexity which represents a spatially aggregated shelf sea region. The model simulates the fluxes of nutrient (nitrogen) through the ecosystem from dissolved inorganic (nitrate and ammonia), through plankton, benthos and fish, to birds and mammals, its regeneration through excretion and mineralization of detritus in the water column and sediment, and the physical oceanographic, land-sea, and air-sea exchanges across the geographic boundaries. The model will be adapted to translate Nitrogen to Carbon inasmuch as is feasible. It will be used to explore a range of fishing and environmental scenarios including climate change and changes in fishing.

The second model used is Ecopath with Ecosim (EwE) (led by Jacob Bentley at English Nature (UK) and Dave Reid at the Marine Institute in Ireland. Ecopath is an ecological/ecosystem modelling software suite. EwE has three main components: Ecopath – a static, mass-balanced snapshot of the system; Ecosim – a time dynamic simulation module for policy exploration; and Ecospace – a spatial and temporal dynamic module primarily designed for exploring impact and placement of protected areas. Ecopath is designed as a model to investigate fishery and food web interactions, but will be modified to include the carbon budget aspects of fishing on the ecosystem and food web. Again, this will then be used to explore the same scenarios as will be used in StrathE2E.

The third modelling approach uses EcoTroph, (led by Didier Gascuel at Agrocampus, France). EcoTroph (ET) is articulated around the idea that an ecosystem can be represented by its biomass distribution across trophic levels, the biomass trophic spectrum. The ecosystem functioning is viewed as a biomass flow moving from lower to higher trophic levels, due to predation and ontogenetic processes. Thus, the ecosystem biomass present at a given trophic level may be estimated from two simple equations, one describing biomass flow, the other their kinetics (which quantifies the velocity of biomass transfers towards top predators). Again, this will be used to explore scenarios of climate change and fishing and the potential impacts on carbon sequestration.

The key common factor for these three modelling approaches is that the great bulk of fishing actually occurs in shelf seas, and not the open ocean. But the understanding of the functioning of the BCP is much less well developed than for the open ocean. Water column attenuation of deadfall or faeces will be much less important in these relatively shallow waters. This biological material will also enter the benthic food web where there are many detritovores, in contrast to the deep sea. Finally, the shelf sea sediments are subject to much greater disturbance, and hence possible remineralisation than are the deep ocean sea-beds. This disturbance includes: water movement e.g. currents, tides and turbulence; bioturbation by benthic infauna; and anthropogenic disturbance, predominantly fishing. The aim will be to use these models to help quantify carbon flux, identify the relative importance of that in a local and global scale, and identify how fishing would be expected to perturb that flux and pathway to sequestration.

Implementation Timelines

- **Months 10-18**

The main work in this period will be to adapt the three model systems to provide outputs in terms of carbon flux to the seabed. EwE will focus on the Celtic Sea as a regional sea. StrathE2E will perform a series of regional seas case studies from the Arctic Ocean to the S. Atlantic. Ecotroph will focus on the Atlantic Basin scale. None of these models were specifically designed to quantify carbon flux and will be adapted to do so either stoichiometric relations between nitrogen and carbon fluxes in the case of StrathE2E, or biomass and carbon for EwE and EcoTroph. Candidate scenarios will be prepared for each of the models based on outputs from other WP, from new literature and from consultations with stakeholders under WP8.

- **Months 18-36**

The main work in this period will focus on testing and extending the scenarios developed in months 10-18. The aim will be to use similar scenarios in all three model systems within the constraints of each system. For instance, EwE will use a range of functional groups that range from individual species, principally commercial species, to species grouped by their functional role, biology or morphology. Ecospace will be used to describe the spatial distribution of the carbon flux in response to spatially variable fishing, and biomass. StrathE2E uses broader functional groups e.g. demersal or pelagic fish, and has a coarser spatial scale, but has the advantage of covering the complete ecosystem from nitrogen (carbon) to fishing. Ecotroph considers only biomass by trophic level, but can be carried out at a basin scale.

- **Months 36-48**

The main work in this period will be to synthesise the findings from the three model systems and identify common features of the outcomes that can be used for policy advice. This will also allow a contrasting of the outcomes from the models helping to identify structural (model design) uncertainties. During this period, we will also aim to link the findings of other aspects of OceanICU with the model outputs. For example, including findings from Task 5.1. on the impact of fishing on the seabed and resuspension of carbon from it. This may also allow scenarios derived from reduction of fishing impacts on the seafloor and concomitant changes in the food web, and carbon cycling and remineralisation.

3.4. Task 5.4: Impacts of fishing on carbon sequestration in the off-shelf ecosystem

Task 5.4 will examine the role of fishing on carbon sequestration in the off-shelf seas context. This will be carried out using two modelling systems.

In the off-shelf context, we are using two model systems to examine the effects of fishing. The first is the Spatial Ecosystem and Population Dynamics Model – SEAPODYM. This is a numerical model developed for investigating physical-biological interactions between fish populations and the ocean pelagic ecosystem. The focus of this work in OceanICU is on actual current fishing for small and large pelagic fish (e.g. mackerel and tuna respectively), and will examine both direct carbon aspects, as in the removal of biomass, and indirect effects via the food web interactions. This work is being led by Patrick Lehodey. The second model system is FEISTY, which is a temporally dynamic, spatially explicit, mechanistic model of size-structured forage, large pelagic, and demersal fish functional types and an unstructured benthic invertebrate biomass pool. Fish functional types are defined by their maximum size, habitat, and prey preference. This work is focused on potential fishing for mesopelagic fish. There is currently little or no fishing on these fish, but their populations are estimated as being substantial (1-10 Gt) and are a major part of the BCP.

The timelines for this work are from months 1-44 when the results will be compiled in D5.3 “A report summarising quantitative effects of key processes on the ocean C cycle based on analyses conducted in the WP”. All the modelling work cited has started and is in the development phase.

Implementation Timelines

- **Months 10-18**

The main work in this period will be to develop and adapt the two model systems to provide outputs in terms of carbon flux through the water column to the seabed. For SEAPODYM, this includes a contribution to the analyse of the impact of the World largest tuna fisheries in the Pacific Ocean on the sequestration of carbon by sinking tuna carcasses. Then, the SEAPODYM low and mid trophic levels modelling will be further developed with one additional functional group for the vertically migrant mesopelagic zooplankton. A historical hindcast global simulation will be produced with forcing variables generated by the coupled ocean physical-biogeochemical model NEMO-PISCES and the atmospheric forcing ERA5. The new zooplankton parameterisation will be calibrated using day time and night time observations (HOT, BATS, PAPA, Channel). For FEISTY this will include adaptation to include mesopelagic fish and fishing on those. We will also provide a Fortran-R package including an online Shiny simulator that will include fishing particularly on mesopelagics. The aim will also be to provide a full 2-way coupling between FEISTY and UVic (and possibly FABM later). We will also start to develop scenarios of fishing and climate change that can be tested in the completed models.

- **Months 18-36**

The main work in this period will focus on further model developments to include fishing impact on specific mesopelagic group or species, model parameters optimisation and validation of predicted biomass, and testing and extending the scenarios developed in months 10-18.

For SEAPODYM, this will include additional observation data sets to be used for testing new optimisation methods and for validating the micronekton functional groups. A new model component will be developed to generate fishing scenarios on mesopelagic species. All these new changes will be first developed in a version without transport, that will be tested with time series data at several oceanographic stations and from other appropriate sources (e.g., mesopelagic research cruises). Climate change simulations using several climate model forcings will be prepared to provide an ensemble of future projections of zooplankton and micronekton. These forcings and outputs will be made available to project partners.

For FEISTY the work will first be to implement the model into the UVic Earth System Model using the FABM interface to achieve full two-way coupling. We will then compare the 2-way coupled model output with existing one-way coupled model output. Further, the FEISTY model will be integrated in the carbon cycle with respiration and faecal pellets, and calculate the total carbon sequestration. We will then develop fishing scenarios, mainly focused on fishing large and small pelagic species and explore the consequences for carbon sequestration of fishing.

- **Months 36-48**

The main work in this period will be to finalise the analyses of simulation outputs and to synthesise the findings with a particular attention to cross comparisons between the two models.

3.5. Task 5.4: Impacts of fishing on carbon sequestration in the off-shelf ecosystem

Task 5.4 will study the impacts of fishing on carbon sequestration in the off-shelf ecosystem. This will use two model systems to examine the effects of fishing. The first is the Spatial Ecosystem and Population Dynamics Model – SEAPODYM. This is a numerical model developed for investigating physical-biological interactions between fish populations and the ocean pelagic ecosystem. The focus of this work in OceanICU is on actual current fishing for small and large pelagic fish (e.g. mackerel and tuna respectively), and will examine both direct carbon aspects, as in the removal of biomass, and indirect effects via the food web interactions. This work is being led by Patrick Lehodey. The second model system is FEISTY, which is a temporally dynamic, spatially explicit, mechanistic model of size-structured forage, large pelagic, and demersal fish functional types and an unstructured benthic invertebrate biomass pool. Fish functional types are defined by their maximum size, habitat, and prey preference. This work is focused on potential fishing for mesopelagic fish. There is currently little or no fishing on these fish, but their populations are estimated as being substantial (1-10 Gt) and are a major part of the BCP.

3.6. Task 5.5: Transfer knowledge to DSTs

Task 5.5 will inform WP7 about useful model scenarios for the DSTs and in collaboration with WP7 develop a suitable workflow to transfer information to the DSTs. Task 5.5 starts at M28 and finishes M45 of the project.

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3.7. Critical risks for implementation

Table 4: Critical risks of WP5 linked to deliverables

Deliverables	Responsible	Critical risk for Implementation	Mitigation
D5.1 Implementation Plan	MI	None	None needed
D5.2 Summary of material passed to WP7 in M5.1 that quantitatively links the intensity of human pressure to C cycle impacts in all four areas	MI	Low	The use of multiple models in this WP should mitigate any risk in the operation of any one model system
D5.3 Summary of material passed to WP7 in M5.2 that reports the final analysis of how fishing and Industrial processes impact the C cycle from WP5.1 to 5.4 transferred to WP7 in M5.2	MI	Low	The use of multiple models in this WP should mitigate any risk in the operation of any one model system
D5.4 Summary of all work within the WP including estimates of how industrial processes control ocean C in the modern ocean with submitted manuscripts	MI	Low	The use of multiple models in this WP should mitigate any risk in the operation of any one model system

3.8. Expected results

The results proposed in this section will feed a master document summarizing Key Exploitable Results and KPIs, which will serve to measure the progress, but also the outcomes and potential impact of OceanICU's research within the project's life and after its end.

Table 5: Expected results from WP5

#Identifier	Result	Partner responsible	Expected time
R5.1	Synthesis of mining-induced impacts on ocean C cycles processes (water column and sediments) and recommendations for ISA's Mining Code	GEOMAR	31 October 2026
R5.2	Synthesis of fisheries impacts on Northsea coupled biological-biogeochemical processes	NIOZ	01 January 2027
R5.3	Synthesis of the conclusions from the model and scenario simulations of the effect of changing fishery exploitation patterns	MI	31 October 2026

3.9. Gantt Chart

Task	0-6	7-12	13-18	19-24	25-30	31-36	37-42	43-48	49-54	55-60
5.1 Deep-seabed mining impacts										
(1) Develop model scenarios										
(2) Water-column plume impact modelling										
(3) benthic impact modelling										
5.2 Bottom-trawling impacts										
(1) Test biological part of model										
(2) Biological-biogeochemal modelling										
(3) NEMO-ERSEM coupling										
5.3 Off-shelf fisheries										
(1) Adapt models for specific carbon flux estimations										
(2) Development and testing of scenarios										
(3) Synthesizing results and carry out any additional analysis needed										
5.4 On-shelf fisheries										
(1) Adapt models for specific carbon flux estimations										
(2) Development and testing of scenarios										
(3) Synthesizing results and carry out any additional analysis needed										
5.5 Transfer to DSTs										
(1) Deliver information on the role of fishing and mining industrial exploitation on carbon sequestration to WP7										

4. WP5 management

4.1. WP5 management structure and routines

Actively and openly in Executive Board meetings, General Assemblies and other OceanICU meetings as required, and remain responsive to requests from all other WPs. WP5 leads will endeavour to produce all requested reports on time, providing sufficient time for feedback and internal review.

4.2. Key performance indicators (KPIs)

These will feed a master document summarizing Key Exploitable Results and KPIs, which will serve to measure the progress, but also the outcomes and potential impact of OceanICU's research within the project's life and after its end.

Table 7 – KPIs to measure the performance of WP5.

Activities	KPI	Status – to date
	Task 5.1	
Interaction with stakeholders in the field of deep-sea mining	Number of presentations	Presentations (side events, posters) at ISA Annual Meetings: March 2023, July 2023
	Task 5.2	
	Task 5.3	
	Task 5.4	

Activities	KPI	Status – to date
Tools to predict the effect of fishing on ocean C cycle	22) Managers in fishing industry aware of impact on C and integrating this into their planning	Presentations to Irish Parliament on carbon and fishing 11 May 2023, and EC 12 June 2023. Also presentation to Fishermen's organization in Killybegs, Ireland 29 September 2023
Task 5.5		

5. Interactions with other WPs

WP5 will interact with WP6, WP7, and WP8.

6. References

- Mouillot D, Derminon S, Mariani G, Senina I, Fromentin J-M, Lehodey P. & M Troussellier (2023). Industrial fisheries have reversed the carbon sequestration by tuna carcasses into emissions. Global Change biology. https://doi.org/10.1111/gcb.16823