Active Chlorophyll fluorescence for autonomous measurements of global marine primary productivity

1. Summary

Marine primary productivity controls ocean food webs and biogeochemical cycles, exerting a strong influence on CO_2 uptake from the atmosphere and global climate. Unprecedented anthropogenic pressure has created an urgent need to understand environmental controls on primary productivity. This, in turn, relies on consistent and coherent measurements across a range of spatial and temporal scales. Productivity estimates from conventional ^{14}C-uptake experiments require discrete bottle sampling (and suffer potential experimental artefacts), while those from mixed layer dissolved gas measurements (O_2, CO_2 etc.) do not directly measure gross photosynthesis, and lack the temporal resolution needed to validate daily remote-sensing observations. Active chlorophyll a (Chla) fluorescence-based measurements can overcome these challenges. First introduced several decades ago, techniques such as Fast Repetition Rate fluorometry have significantly advanced our understanding of environmental controls on phytoplankton physiology and productivity. However, rapidly growing capacity to engineer and deploy sea-going fluorometers now poses a major time-sensitive challenge: Conceptual, operational and computational approaches to extract and interpret fluorescence parameters are rapidly diverging. While an increasing number of (often custom-built) sensors, protocols and processing algorithms is being produced, no standard best practices have been formally adopted by the research community. Rapidly growing data sets may thus become increasingly difficult (perhaps impossible) to reconcile, thereby limiting our capacity to integrate observations over large-scales. This SCOR working group will address this challenge by producing international standards for best-practices in the acquisition and interpretation of active Chl fluorescence data, while also creating a framework for a global synthesis of existing and future data.

2. Scientific Background & Rationale

2.1. Importance of high-resolution primary productivity measurements

Marine primary productivity sets the carrying capacity of oceanic ecosystems and exerts a profound influence on the cycling of nutrients and carbon in the biosphere. Global climate change has created a pressing need to understand the environmental controls on marine productivity, its variability over space and time, and its potential responses to altered upper ocean conditions (Behrenfeld et al. 2006, Moore et al. 2018). Addressing these questions requires consistent and coherent measurements of oceanic primary productivity across a range of scales.

Historically, most measurements of marine primary productivity have come from ship-board ^{14}C incubation methods (e.g. Halsey & Jones 2015). Over the past half century, the oceanographic community has built a large global repository of ^{14}C uptake data (http://www.science.oregonstate.edu/ocean.productivity), and used these to inform our understanding of spatial and temporal trends in marine productivity (Behrenfeld & Falkowski 1997). The ^{14}C method, while highly sensitive and simple in principle, has limitations. Most notably, the technique requires the collection of discrete samples, which limits the spatial resolution of measurements, whilst introducing potential experimental artefacts ('bottle effects') via sample containment.

Over the past two decades, there has been an increasing focus on the use of autonomous sensors to quantify marine primary productivity. Satellite-based algorithms are becoming increasingly used to infer productivity from remotely sensed variables (typically, chlorophyll, carbon, light and sea surface temperature) (e.g. Behrenfeld & Falkowski 1997, Behrenfeld et al. 2015). This approach has the advantage of providing synoptic spatial coverage of the surface ocean, but it requires field-based measurement for parameterization of physiological models and algorithm validation (e.g. Lin et al. 2016). More recently, a number of groups have begun using automated chemical sensors to measure mixed layer dissolved gases (e.g. O_2, N_2, Ar, and CO_2) as tracers of net community productivity. These measurements capture bulk productivity on the time-scale of days to weeks, but do not directly measure gross photosynthetic production or physiological responses, nor do they provide appropriate validation for daily remote-sensing observations.

2.2. Rapid expansion of active chlorophyll fluorometers to assess primary productivity

Active chlorophyll fluorometers were introduced to oceanography in the late 1980s. Seminal papers detailed methods to quantify photosynthetic electron transfer rates (ETR), by resolving the induction of chlorophyll a (Chla) fluorescence following rapid modulation of an excitation light source (Kolber & Falkowski 1993, Kolber et al. 1998). As a component of the photosynthetic process, ETR is inherently coupled to the rate of light-dependent water splitting, oxygen evolution and ATP and NADPH production, and, as such, provides an estimate of gross primary productivity. Early studies demonstrated that ETRs derived from active Chla fluorescence measurements correlated well with parallel ^{14}C-uptake rates (Kolber & Falkowski 1993) and gross oxygen evolution rates (Suggett et al. 2003). Others demonstrated important applications of Chla fluorescence data to understand the physiological status of phytoplankton in situ, including cellular responses to iron limitation (e.g. Kolber et al. 1994).

Motivated by these pioneering studies, and facilitated by technological developments, there was a surge of interest in the application of active fluorometry for oceanic productivity and photo-physiological studies. The first commercially available Fast Repetition Rate Fluorometer (FRRf; and derivative FIRe fluorometers, Gorbunov & Falkowski 2005) instruments were released in the early 2000s (Chelsea Technologies Group Ltd., Satlantic Inc.). Most efforts aimed at further reconciling ETRs with ^{14}C-uptake (Corno et al. 2006, Suggett et al. 2006, Moore et al. 2006), and growing data sets repeatedly demonstrated strong covariance between parallel ETRs and ^{14}C-uptake measurements throughout the world's oceans. However, the results of this work demonstrated that the relationship between these measurements varied depending upon the prevailing phytoplankton taxa and/or environmental conditions (see Suggett et al. 2009, Lawrenz et al. 2013). Within a decade, FRRfs (and FIRe fluorometers) became standard instrumentation on many large-scale oceanographic programs (e.g. Atlantic Meridional Transect; Suggett et al. 2006, Hawaii Ocean Time-Series; Corno et al. 2006), and biogeochemical studies of ocean productivity (e.g. Behrenfeld et al. 2006).

While the application of FRRfs and related active Chla induction instrumentation continues to grow, routine derivation of primary productivity from these measurements still faces significant challenges. Operational and technological constraints, as well as complexities associated with the algorithms used to derive ETRs from raw fluorescence data have hampered efforts to derive robust productivity estimates. A major EU program (PROTOOL) brought together a group of experts in an attempt to develop new and more robust ETR algorithms (Oxborough et al. 2012), whilst also incorporating multi-spectral measurements to better resolve the influences of diverse light harvesting across phytoplankton groups (see Silsbe et al. 2015). These critical developments catalysed renewed interest in the use of FRRf as an oceanographic measurement tool (e.g. Schuback et al. 2017, Zhu et al. 2017). This renewed interest, alongside new technological advances in light sources and detectors (PicoF and mini-FIRe, Lin et al. 2016; Hoadley & Warner 2017), point the way towards global-scale oceanographic deployment of active Chla induction fluorometers, using a new generation of systems on a range of platforms, including ships, gliders, mooring and floats.

Our capacity to quantify the spatial and temporal variability in oceanic primary productivity has thus never been greater. However, ***our rapidly growing capacity to engineer and deploy active Chla induction fluorometers now poses a major time-sensitive challenge***: Conceptual, operational and computational approaches used to extract and interpret fluorescence parameters are rapidly diverging. No standard best practices have yet been formally adopted as a large number of (increasingly custom-built) sensors, protocols and processing algorithms are deployed worldwide. As a result, rapidly growing data sets may become increasingly difficult (if not impossible) to reconcile, thereby limiting our ability to build global data compilations and examine large-scale responses of marine productivity to environmental forcing.

2.3. Need and Timeliness for a SCOR working group

A meeting of world experts in active Chla induction fluorometry was recently held in Sydney (AQUAFLUO II: *Chlorophyll fluorescence in the aquatic sciences*, December 2017). Discussions identified a time-critical need for more robust practices to overcome uncertainties and inconsistencies associated with instrument operation, deployment and data fitting and interpretation. As more groups custom-build Chla induction fluorometers, there remains no objective set of international standards for hardware configurations (e.g. excitation-emission wavelengths) or data analysis protocols, and no conventions to validate and inter-calibrate data from these sensors. **Such inter-comparability is critical if we seek to build a global repository of active fluorescence data**. Practices should be based upon minimal, robust assumptions, with clear information on how taxonomic and environmental factors may affect the choice of operating conditions. Establishing guiding principles and models that will allow comparability across research groups is paramount.

Previous working groups have inter-compared active fluorescence data from different commercially available instruments (e.g., AQUAFLUO 2007; GAP-2008, Suggett et al. 2009; PROTOOL, Silsbe et al. 2015). **These efforts, however, did not include an explicit focus on standardized data collection and analysis, nor did they produce recommendations, best-practice guides and software tools to help non-experts employ this method. Moreover, the rapid development of new cheaper and miniaturised instrumentation, along with a number of conceptual advances in our understanding of chlorophyll fluorescence, has created a need to revisit inter-comparisons of operability and data output.** Progress must be driven the broader community's need to establish and embed standardized operation, data retrieval and reporting/archiving. To this end, our proposed working group will assemble a diverse set of scientists to move the research community forward in the application of active Chla induction fluorometry to understand global-scale patterns in marine productivity.

3. Terms of Reference.

Our proposed working group will work to achieve the following specific objectives.

i. To inter-compare active Chla induction measurements across instruments and approaches, identifying key aspects of instrument configuration, deployment and parameter acquisition that may introduce variability in retrieved data.

ii. To develop, implement and document internationally-agreed best practice for data acquisition, standardised output formats and archiving approaches.

iii. To develop, implement and document internationally-agreed best practice for processing raw fluorescence data to retrieve photosynthetic parameters and primary productivity estimates, taking into account taxonomic and environment factors driving diversity in chlorophyll fluorescence signals in the oceans. From this work we will develop freely available software and documentation to allow non-specialist users to process fluorescence data according to these best practices.

iv. To produce a new synthesis of parallel ^{14}C and active Chla induction measurements that can be used to examine the relationship between these two productivity metrics under a range of field conditions. We will also consider other metrics of Net Primary Production alongside ^{14}C.

v. To develop a global database structure for hosting quality-controlled active Chla induction measurements, creating standards for data and meta-data collection, submission and archiving.

vi. To build a framework through which in situ active Chla induction data can be used to validate and refine relevant remote sensing measurements (e.g. sun-induced fluorescence yields).

vii. To share knowledge and transfer skills in instrumentation, best practice, quality control and data stewardship with the rapidly expanding user community in developing nations.

4. Working Plan and Time-line

We will meet our objectives via two dedicated in-person meetings, and additional satellite meetings and video conferences focused on implementing and/or delivering our various objectives, and managing the overall project.

Year 1: Kick-off meeting; laboratory inter-comparison study

Objectives i-ii. We will conduct a SCOR-funded laboratory inter-calibration of the state-of-the-art instrumentation, covering the broadest range of commercial and custom hardware and software (FRRf, FRRf-type single pulse, FRRf-flash, LIFT; as well as mini-FIRe and PicoF). This exercise will examine inter-comparability among existing configurations, studying the effects of various sources of variability (hardware and software) on parameter retrieval. We will conduct this exercise at a relatively central location amongst the WG members (likely Vancouver) using a range of marine phytoplankton cultures (with different pigment complements, cell size, taxonomic group) grown under various experimental conditions, including light and nutrient availability.

We will develop a standard set of protocols, including hardware configurations, parameter selection, algorithm assumptions, data formatting, sample collection/treatment. All participants will contribute in their various expertise to a user guide and best-practices report. This work will also likely lead to a significant peer-reviewed publication.

We will also begin to consider how challenges in ship-board deployment may potentially limit capability to meet best practice. This will be addressed, in part, through a parallel set of experiments focusing on known variables (e.g. dark exposure time) that create potential for uncertainty in field-based measurements. Thorough field tests addressing specific at sea deployment challenges be addressed in year 2.

Year 2: Field evaluations of best-practice

An annual meeting will be conducted in year 2 to evaluate project progress. As Working Group members will likely be required to fund their participation, this will be timed to coincide with a large international meeting such as ASLO. Full video conferencing facilities will be made available to maximize participation among all members.

The focus for this second year is:

<u>Objectives i-ii and iv</u>. Working Group members will critically assess application of 'best practice' (developed from the initial laboratory cross-instrument screening) to their own at-sea deployments. Where WG members are able to exploit existing funded opportunities for oceanographic fieldwork, 'best practice' will be evaluated relative to other possible field-deployable configurations. The goal of this is to (a) examine precision and accuracy achievable through a universally applied 'best practice' under any given scenario (e.g. ultra-oligotrophic waters) and specific instrumentation or mode of deployment (e.g. profiling versus underway). Exercises will also include a standardized comparison of FRRf-based estimates of productivity against parallel NPP (^{14}C measurements) as an independent productivity benchmark. This work will be conducted independently by WG members, following standard protocols established by the group in year 1, including the collection of ancillary data that can be used to interpret results.

These field-based evaluations will enable us to examine how 'best practice' developed from the laboratory can scale to field applications, and to recommend modified approaches for the collection of robust and inter-comparable field studies. The work will also lead to a new synthesis of parallel ^{14}C-FRRf measurements that can be used to analyse the relationship between these two productivity metrics (and potentially others) when obtained using standardized methodologies. All participants will contribute their expertise to compile these results into a report best-practices guide (objectives ii-iii), and a significant peer reviewed article.

Year 3: Begin 'legacy phase' through software and database development

<u>Objectives iii-v</u>. A SCOR funded annual meeting in year three will focus on developing the software and database 'legacy' phase. Based on the documents from objectives (i-iv) detailing the optimised workflows for processing and parameterising raw fluorescence data, we will initially conceptualise and then produce an open source software platform for broad scale and cross-

instrument data processing. We envisage that this will take the form of a "CO2-sys" type product, enabling user selectable algorithms, and ensuring that 'first order' data sets (e.g. raw induction curves) are archived in order to enable re-processing of data at a future date. In this way, users will be able to select different specific parameterisation routines, with the flexibility needed to include data from across different approaches in deployment and configuration. The long-term motivation for this work will be the production of a global database (likely hosted by NASA), designed to archive both raw data and derived parameters. We envisage a data entity similar to (or as part of) NASA's SeaBASS archive (https://seabass.gsfc.nasa.gov) built on defined standardised parameters (and units etc.), paralleling one already in existence for carbon-uptake data (http://www.science.oregonstate.edu/ocean.productivity/field.data.fl.readme.php). Significantly, we have developed this proposal with specific input from Chris Proctor and Susanne Craig at NASA. They are not listed as WG members, but they have both expressed strong interest in this work, and are expected to participate in relevant meetings, with support from NASA.

Year 4: Remote sensing integration and public release

Objective v-vi: As part of our final meeting, we will formalise all documentation and (beta-version) software for public release as part of an international and community wide meeting. For example, dedicated workshops and events at ASLO or Ocean Optics (and/or a specialist meeting, e.g. AQUAFLUO III). We will seek independent funding (e.g. NASA) to support both broad attendance from amongst the WG but also to support outreach and visibility. Importantly, this meeting will enable us to disseminate ('launch') all material to the broadest user base, thereby transforming capacity and creating the maximum visibility. Releases will also be accompanied by press releases and launches through the Working Groups' institutions and regional networks. Working closely with NASA, we will look to host standard protocol documentation and tools through the IOCCG website as well as data archival portals.

A secondary component of this final meeting will be a one-day session for WG members to build a framework enabling non-specialist users to exploit growing databases with remotely retrieved (e.g. satellite) bio-optical data. We will produce a document detailing steps needed (and data sets required) to validate and potentially refine remotely sensed fluorescence data products, with initial proof of concept data collected earlier in this working group (Year 2).

5. Deliverables

Addressing our objectives will result in the following deliverables:

i. Open access documents fully detailing (a) Standard Operating Procedures (and "Best Practices") that can be applied commonly across (and/or account for differences amongst) instrument type, instrument configuration, and deployment platform; and (b) framework to apply chlorophyll fluorescence data sets to validate and potentially refine remotely sensed fluorescence data products.

ii. Open source "CO2-sys" type data analysis tool for fluorescence induction curve processing.

iii. New data set of NPP (^{14}C) – active Chla induction inter-comparisons across a variety of oceanographic regimes, conducted with standardized methodology

iv. Web-based global data archival portal (and associated information repository) for data extraction according to user defined temporal-spatial criteria

v. Peer reviewed papers that report instrument inter-comparison exercises from both the laboratory and field.

6. Capacity Building

Fundamentally, our Working Group approach and deliverables provide broad-scale (global) capacity building towards all current users of existing active Chla induction instrumentation. However, by providing a series of standardised operating procedures and open source tools to both collect, parameterise and archive data, we aim to expand the global user group for active fluorescence data, enabling non-specialized users to deploy a highly sophisticated method. The open source nature of the software and archiving tools, as well as the community-wide release through global networks ensure that the outputs have the furthest possible reach. Importantly, our group includes Working Group Members from Developing Countries (e.g. Brazil, South Africa) as well as early career stages to embed potential capacity building from the outset of the project.

Depending on co-funding that can be sourced for the year 4 launch, we see this meeting as an opportunity to include a training event of the new products ('CO2sys'-type data processing tool and web-based archive) to the broader (and prospective future) user communities.

7. Composition of Working Group

Our Working Group will be comprised of 10 Full and 10 Associate Members that bring collective expertise from biophysics, photosynthesis, bio-optics (including remote sensing), oceanography, data archiving, and instrument and software development. Full Members are primarily responsible for the delivery of our objectives, with the Associate Members providing important input on key specific areas. Our Full members represent 8 different nations, including 1 emerging/developing nation (South Africa) and 2 early career researchers (Thomalla, Schuback). Similarly, our contributing members represent 7 different nations with further representatives from developing nations (Brazil) and early career researchers (Silsbe, Varkey). Finally, we also include a list of additional experts (7.3. Others), with particularly specialised skill sets and who have expressed interest in participating in one or more of the dedicated workshops. We fully recognize some gender imbalance in the overall WG composition, but note that half of our Associate Members are female. The oceanographic active Chl fluorescence field was initially male-dominated from its inception, and we are committed to addressing this gender imbalance moving forward.

7.1. Full Members

Name	Gender	Place of work	Expertise relevant to proposal
David Suggett (Co-chair)	M	Australia	Active chlorophyll fluorescence; phytoplankton physiology
Philippe Tortell (Co-chair)	M	Canada	Sea-going autonomous primary productivity
Zbignew Kolber	M	USA	FRRf instrument development (LIFT); phytoplankton physiology; data analysis and computation

Sandy Thomalla	F	South Africa	Deployment platforms; remotely sensed fluorescence; data analysis, visualisation and archiving
Kevin Oxborough	M	UK	FRRf instrument development (FRRf); phytoplankton physiology; data analysis and computation
Maxim Gorbunov	M	USA	FRRf instrument development (Pico-F); phytoplankton physiology; data analysis and computation
Nina Schuback	F	Switzerland	Active chlorophyll fluorescence; phytoplankton physiology
Tetsuichi Fujiki	M	Japan	FRRf instrument development (FRRf-flash); phytoplankton physiology; data analysis and computation
Jacco Kromkamp	M	Netherlands	Active chlorophyll fluorescence; Primary productivity; phytoplankton physiology; deployment platforms
Mark Moore	M	UK	Active chlorophyll fluorescence; phytoplankton physiology; data parameterisation and analysis

7.2. Associate Members

Name	**Gender**	**Place of work**	**Expertise relevant to proposal**
Greg Silsbe	M	USA	Active chlorophyll fluorescence; data analysis and computation; data analysis, visualisation and archiving; Remote sensing
Kim Halsey	F	USA	Primary productivity; phytoplankton physiology, ^{14}C applications
Ondrej Prasil	M	Czech Republic	Primary productivity; phytoplankton physiology
Doug Campbell	M	Canada	Active chlorophyll fluorescence; Primary productivity; phytoplankton physiology
Aurea Ciotti	F	Brazil	Primary productivity; Sea-going autonomous primary productivity
Yannick Huot	M	Canada	Active chlorophyll fluorescence; remote sensing and bio-optics; data handling
Anna Hickman	F	UK	Bio-optics and fluorescence; remote sensing; modelling
Stefan Simis	M	UK	Active chlorophyll fluorescence; remote sensing and bio-optics; data handling; open source fluorometer hardware
Ilana Berman-Frank	F	Israel	Primary productivity; phytoplankton physiology
Deepa Varkey	F	Australia	Photosynthesis, Chl Fluorescence and data analytics (functional genomics)

7.3. Others:

Additional experts with specialised skill-sets will participate in one or more of the dedicated workshops. All of these individuals have confirmed their interest in our work.

Susanne Craig	F	USA (NASA)	Active chlorophyll fluorescence, Remote sensing Data archiving
Chris Proctor	M	USA (NASA)	Active chlorophyll fluorescence, Remote sensing Data archiving
Paul Falkowski	M	USA	Active chlorophyll fluorescence; Primary productivity; phytoplankton physiology;
Kenneth Hoadley	M	USA, Australia	Active chlorophyll fluorescence; open-source fluorometer development; phytoplankton physiology;

8. Working Group contributions

Tetsuichi FUJIKI brings unique *in situ* FRRf instrumentation for inter-comparison and parameter retrieval (objectives i-iii). Access to field-based deployments in the Pacific (including autonomous platforms, and miniaturised sensors for gliders and floats) provides essential contributions to objectives ii-v.

Maxim GORBUNOV brings key expertise in hardware and software development (including data analysis and algorithm development) of various instrument approaches (FRRf, FIRe, PicoF), and applications of these instruments to different ocean systems (polar, temperate and tropical), thus contributing to objectives i-v.

Jacco KROMKAMP has key expertise developing autonomous productivity measurements (including ships of opportunity) and fluorometer inter-comparisons, contributing significantly to objectives i-v. He will also contribute to database development and data archival through parallel efforts from previous (e.g. leading PROTOOL) and current EU projects examining coastal primary productivity (objective vi).

Zbigniew KOLBER will contribute to identifying fluorescence properties indicative of photo-physiological performance, and assessing the utility of these properties as a proxy for primary production (objectives i-ii, iv)**.** His background in developing new FRR fluorescence instruments (FRRf, LIFT) and data processing algorithms, will be critical to the project.

Mark MOORE will contribute to objectives i-iv, and help us in capacity building (objective vii), based on his previous work with groups in India. In addition to attending to both laboratory and field-based evaluation exercises, Moore will contribute equipment and data from a NERC UK funded autonomous active chlorophyll fluorometer development project ('STAFES-APP') to all activities.

Kevin OXBOROUGH has expertise developing single turnover active chlorophyll fluorometer systems for installation on marine autonomous systems. He will focus on objectives i-iii and v, with some involvement in objectives iv, vi and/or vii. His background in developing new fluorescence algorithms from terrestrial and aquatic organisms, as well as new software and hardware, will be critical.

Nina SCHUBACK will contribute significantly to instrument inter-comparisons and reconciliation of electron transfer rates with NPP (objectives i-ii, iv), in particular through her specialist focus and field opportunities in polar systems. Her computational and data handling skills will also contribute to objectives v, vii.

David SUGGETT will be responsible for joint-management and coordination of the overall project and thus contribute to the delivery of all activities. His specific expertise and unique instrumentation pool (e.g. FRRs, LIFT, multi-speQ) is essential to laboratory inter-comparisons and their associated output (i-iv, vi) and in the synthesis of larger data sets for objectives v-vi.

Sandy THOMALLA will contribute to *in situ* application of instrumentation to guide best practice, and in particular through autonomous deployments (objectives ii, iv). Her expertise in development and validation of ocean colour algorithms will contribute to handling and archiving of large data sets, and validation of sun-induced fluorescence observations from satellites (objectives v, vi).

Philippe TORTELL will be responsible for joint-management and coordination of the overall project and thus contribute to the delivery of all activities. His expertise in development and deployment of sea-going autonomous productivity measurements will contribute to all objectives. He will likely organize and host the first full WG meeting and associated inter-comparison work.

9. Relationship to other international programs and SCOR Working groups.

Some of the very first SCOR working groups, more than 50 years ago, focused on understanding large-scale patterns in oceanic productivity; WG3 "*Measurements of the Productivity of the Sea and of the Standing Crops of Phytoplankton and Zooplankton (renamed Biological Production of the Sea)*", WG20 "*Radiocarbon Estimation of Primary Production (approved in 1965; joint with ICES and UNESCO)*", and WG 4 "*Estimation of Primary Production under Special Conditions*". Since that time, new technologies for ocean observations have radically transformed our ability to quantify marine productivity over a range of scales. Yet, no single SCOR Working Group has been dedicated to standardising and ensuring best practice of rapidly expanding autonomous productivity measurements.

As stated in section 2.3, previous working groups have attempted to inter-compare active fluorescence data from different commercially available instruments (e.g., AQUAFLUO 2007; GAP-2008, Suggett et al. 2009; PROTOOL, Silsbe et al. 2015). These past efforts highlight major global demand and incentive to reconcile data from across an ever evolving and growing instrument base. However, they did not include an explicit focus on the need for standardized data collection and analysis, nor did they produce best-practices guides and software tools for wide distribution to non-experts. Our WG proposes to further advance the field by producing a singular set of openly available recourses needed to generate large inter-comparable data sets of active fluorescence (FRRf and FRRf-like) measurements. Such efforts mirror programs that broadly exist for global bio-optical data sets and ^{14}C uptake data (e.g. Prof. Mike Behrenfeld, Oregon State University; http://www.science.oregonstate.edu/ocean.productivity/field.data.fl.readme.php). Our objective to better reconcile field-based fluorescence data with remotely sensed fluorescence parallels efforts initiated by researchers working in terrestrial systems (e.g. SpecNet, http://specnet.info/index.php). Several of our objectives (e.g. v-vi) will directly leverage with the EU-funded Horizon 2020 project MONOCLE (www.monocle-h2020.eu; coordinated by Stefan Simis – Associate member of this proposed WG), which is already developing state-of-the-art networking for in situ sensors, links with satellite observations, data visualisation and analysis tools (e.g. anomaly detection), which can be applied to instrumentation once best-practice is established.

By introducing quality control and best practice procedures into rapidly growing capability to measure key ocean biogeochemical metrics, we parallel SCOR WG 142 "*Quality Control Procedures for Oxygen and Other Biogeochemical Sensors …*", WG143 "*Dissolved N_2O and CH_4 measurements…*" and WG148 "*International Quality Controlled Ocean Database…*". As a founding member of WG143 (which is now coming to an end), Tortell has significant experience with the implementation of a successful SCOR program. Similarly, our focus on developing inter-comparable data sets to support a global database compliments other Working Groups, such as WG147 "*Towards comparability of global oceanic nutrient data (COMPONUT)"* and WG149 "*Changing Ocean Biological Systems (COBS): …*". Finally, by providing a means to standardise and archive active fluorometry data, we will support broader implementation of the growing instrument base of active fluorometers into existing global sampling programs. This theme underpins other Working Groups, e.g. WG154 "*Integration of Plankton-Observing Sensor Systems to Existing Global Sampling Programs (P-OBS)".*

10. Key References

Behrenfeld MJ, Falkowski PG (1997) Photosynthetic rates derived from satellite-based chlorophyll concentration. Limnology and Oceanography 42: 1-20.

Behrenfeld MJ, *et al*. (2016). Revaluating ocean warming impacts on global phytoplankton. Nature Climate Change, 6, 323–330.

Behrenfeld MJ, *et al.* (2006) Controls on tropical Pacific Ocean productivity revealed through nutrient stress diagnostics. Nature 442: 1025 1028.

Corno G, *et al.* (2006) Assessing primary production variability in the North Pacific sub-tropical gyre: a comparison of Fast Repetition Rate fluorometry and ^{14}C measurements. Journal of Phycology 42: 51-60.

Gorbunov MY, Falkwoski PG (2005) Fluorescence induction and relaxation (FIRe) technique and instrumentation for monitoring photosynthetic processes and primary production. In *Aquatic Ecosystems, Photosynthesis: Fundamental Aspects to Global Perspectives*.

Halsey KH, Jones BM (2015). Phytoplankton strategies for photosynthetic energy allocation. Annual Review of Marine Science 7: 265-297.

Hoadley KD, Warner ME (2017) Use of open source hardware and software platforms to quantify spectrally dependent differences in photochemical efficiency and functional absorption cross section within *Symbiodinium* spp. Frontiers in Marine Science 4: 365.

Kolber ZS, *et al.* (1994) Iron limitation of phytoplankton photosynthesis in the Equatorial Pacific Ocean. Nature 371: 145 149.

Kolber ZS, Falkowski PG (1993) Use of active fluorescence to estimate phytoplankton photosynthesis in situ. Limnology and Oceanography 38: 1646 1665.

Kolber ZS, *et al.* (1998) Measurements of variable chlorophyll fluorescence using fast repetition rate techniques. Biochemica Biophysica Acta 1367: 88-106.

Lawrenz E, *et al.* (2013) Predicting the electron requirement for carbon fixation in seas and oceans. PLoS One 8: e58137.

Lin H, *et al.* (2016) The fate of photons absorbed by phytoplankton in the global ocean. Science 351: 264-267.

Moore CM, *et al.* (2006) Phytoplankton photo-adaptation and acclimation responses to environmental gradients in a shelf sea. Limnology and Oceanography 51: 936-949.

Moore JK, *et al.* (2018). Sustained climate warming drives declining marine biological productivity. Science 359: 1139-1143.

Oxborough K, *et al.* (2012) Direct estimation of functional PSII reaction center concentration and PSII electron flux on a volume basis: a new approach to the analysis of Fast Repetition Rate fluorometry (FRRf) data. Limnology and Oceanography: Methods 10: 142-154.

Schuback N, *et al.* (2017) Primary productivity and the coupling of photosynthetic electron transport and carbon fixation in the Arctic Ocean. Limnology and Oceanography 62: 898–921.

Silsbe GM, *et al.* (2015) Toward autonomous measurements of photosynthetic electron transport rates: An evaluation of active fluorescence-based measurements of photochemistry. Limnology and Oceanography Methods 13: 138-155.

Suggett DJ, *et al.* (2009) Comparing electron transport with gas exchange: Parameterising exchange rates between alternative photosynthetic currencies for eukaryotic phytoplankton. Aquatic Microbial Ecology 56: 147-162.

Suggett DJ, *et al.* (2006) Photosynthetic electron turnover in the tropical and subtropical Atlantic Ocean. Deep-Sea Research II 53: 1573-1592.

Suggett DJ, *et al.* (2003) Fast repetition rate and pulse amplitude modulation chlorophyll a fluorescence measurements for assessment of photosynthetic electron transport in marine phytoplankton. European Journal of Phycology 38: 371-384.

Zhu Y, *et al.* (2017) Relationship between light, community composition and the electron requirement for carbon fixation in natural phytoplankton. Marine Ecology Progress Series 580: 83-100.

Appendix
For each Full Member, indicate 5 key publications related to the proposal.

Tetsuichi FUJIKI

Fujiki T, Takagi H, Kkimoto K, Kurasawa A, Yuasa T, Mino Y (2014) Assessment of algal photosynthesis in planktic foraminifers by Fast RepetitionRrate fluorometry. Journal of Plankton Research 36: 1403-1407.

Fujiki T, Matsumoto K, Mino Y, Sasaoka K, Wakita M, Kawakami H, Honda MC, Watanabe S, Saino T (2014) Seasonal cycle of phytoplankton community structure and photo-physiological state in the western subarctic gyre of the north pacific. Limnology and Oceanography 59(3): 887-900.

Fujiki T, Matsumoto K, Watanabe S, Hosaka T, Saino T (2011) Phytoplankton productivity in the western subarctic gyre of the north pacific in early summer 2006. Journal of Oceanography 67: 295-303.

Fujiki T, Hosaka T, Kimoto H, Ishimaru T, Saino T (2008) In situ observation of phytoplankton productivity by an underwater profiling buoy system: use of Fast Repetition Rate (FRR) fluorometry. Marine Ecology Progress Series 353: 81-88.

Fujiki T, Suzue T, kimoto H, Saino T (2007) Photosynthetic electron transport in Dunaliella tertiolecta (chlorophyceae) measured by Fast Repetition Rate fluorometry: relation to carbon assimilation. Journal of Plankton Research 2: 199-208.

Maxim GORBUNOV

Lin H, Kuzminov FI, Park J, Lee SH, Falkowski PG, Gorbunov MY (2016) The fate of photons absorbed by phytoplankton in the global ocean. Science 351: 264-267.

Gorbunov MY, Kuzminov FI, Fadeev VV, Kim JD, Falkowski PG (2011) A kinetic model of non-photochemical quenching in cyanobacteria. Biochimica et Biophysica Acta (BBA)-Bioenergetics 1807: 1591-1599.

Gorbunov MY, Falkwoski PG (2005) Fluorescence induction and relaxation (FIRe) technique and instrumentation for monitoring photosynthetic processes and primary production. Van der Est, D. Bruce (Eds.), Aquatic Ecosystems, Photosynthesis: Fundamental Aspects to Global Perspectives, Alliance Communications Group, Lawrence KS.

Gorbunov MY, Falkowski PG, Kolber ZS (2000) Measurement of photosynthetic parameters in benthic organisms in situ using a SCUBA ‐ based Fast Repetition Rate fluorometer. Limnology and Oceanography 45: 242-245.

Gorbunov MY, Kolber ZS, Falkowski PG (2000) Measuring photosynthetic parameters in individual algal cells by Fast Repetition Rate fluorometry. Photosynthesis Research 62: 141-153.

Jacco KROMKAMP

Aardem HM, Rijkeboer M, Lefebvre A, Veen A, Kromkamp JC (2018) High resolution in situ measurements of phytoplankton photosynthesis and abundance in the Dutch North Sea. Ocean Science Discussions (Open Access In Review; Pre-print: https://doi.org/10.5194/os-2018-21).

Silsbe GM, Oxborough K, Suggett DJ, Forster RM, Ihnken S, Komárek O, Lawrenz E, Prášil O, Röttgers R, Sicner M, Simis S, Van Dijk MA, Kromkamp JC (2015) Toward autonomous measurements of photosynthetic electron transport rates: An evaluation of active fluorescence-based measurements of photochemistry. Limnology and Oceanography Methods 13: 138-155.

Lawrenz E, Silsbe G, Capuzzo E, Ylöstalo P, Forster RM, Simis SGH, Prášil O, Kromkamp J, Hickman AE, Moore CM, Forget M-H, Geider RJ, Suggett, D.J. (2013) Predicting the electron requirement for carbon fixation in seas and oceans. PLoS One 8: e58137.

Silsbe GM, Kromkamp JC (2012) Modeling the irradiance dependency of the quantum efficiency of photosynthesis. Limnology and Oceanography: Methods 10: 645-652.

Kromkamp JC, Forster RM (2003) The use of variable fluorescence measurements in aquatic ecosystems: differences between multiple and single turnover measuring protocols and suggested terminology. European Journal of Phycology 38: 103-112.

Zbigniew KOLBER

Kolber ZS, Klimov D, Ananyev G, Rascher U, Berry J, Osmond B (2005). Measuring photosynthetic parameters at a distance: Laser Induced Fluorescence Transient (LIFT) method for remote measurements of PSII in terrestrial vegetation. Photosynthesis Research 84: 121-129

Kolber ZS, Van Dover CL, Niederman RA, Falkowski PG (2000) Bacterial photosynthesis in surface waters of the open ocean. Nature 407, 177-179.

Kolber ZS, Prasil O, Falkowski PG (1998) Measurements of variable chlorophyll fluorescence using fast repetition rate techniques. I. Defining methodology and experimental protocols. Biochemica Biophysica Acta 1367: 88-106.

Kolber ZS, Barber RT, Coale KH, Fitzwater SE, Greene RM, Johnson KS, Lindley S, Falkowski PG (1994) Iron limitation of phytoplankton photosynthesis in the Equatorial Pacific Ocean. Nature 371: 145 149.

Kolber ZS, Falkowski PG (1993) Use of active fluorescence to estimate phytoplankton photosynthesis in situ. Limnology and Oceanography 38: 1646 1665.

Mark MOORE

Macey AI, Ryan-Keogh T, Richier S, Moore CM, Bibby TS (2014) Photosynthetic protein stoichiometry and photophysiology in the high latitude North Atlantic. Limnology and Oceanography 59: 1853-1864.

Browning TJ, Bouman H A, Moore CM (2014) Satellite-detected fluorescence: Decoupling nonphotochemical quenching from iron stress signals in the South Atlantic and Southern Ocean. Global Biogeochemical Cycles 28: 510-524.

Lawrenz E, Silsbe G, Capuzzo E, Ylöstalo P, Forster RM, Simis SGH, Prášil O, Kromkamp J, Hickman AE, Moore CM, Forget M-H, Geider RJ, Suggett, D.J. (2013) Predicting the electron requirement for carbon fixation in seas and oceans. PLoS One 8: e58137.

Oxborough K, Moore CM, Suggett DJ, Lawson T, Chan HG, Geider RJ (2012) Direct estimation of functional PSII reaction center concentration and PSII electron flux on a volume basis: a new approach to the analysis of Fast Repetition Rate fluorometry (FRRf) data. Limnology and Oceanography: Methods 10: 142-154.

Moore CM, Suggett DJ, Hickman AE, Kim YN, Harris G, Sharples J, Geider RJ, Holligan PM (2006) Phytoplankton photo-adaptation and acclimation responses to environmental gradients in a shelf sea. Limnology and Oceanography 51: 936-949.

Kevin OXBOROUGH

Silsbe GM, Oxborough K, Suggett DJ, Forster RM, Ihnken S, Komárek O, Lawrenz E, Prášil O, Röttgers R, Sicner M, Simis S, Van Dijk MA, Kromkamp JC (2015) Toward autonomous measurements of photosynthetic electron transport rates: An evaluation of active fluorescence-based measurements of photochemistry. Limnology and Oceanography Methods 13: 138-155.

McKew BA, Davey P, Finch SJ, Hopkins J, Lefebvre SC, Metodiev MV, Oxborough K, Raines CA, Lawson T, Geider RJ (2013) The trade-off between the light-harvesting and photoprotective functions of fucoxanthin-chlorophyll proteins dominates light acclimation in Emiliania huxleyi (clone CCMP 1516). New Phytologist 200: 74-85.

Oxborough K, Moore CM, Suggett DJ, Lawson T, Chan HG, Geider RJ (2012) Direct estimation of functional PSII reaction center concentration and PSII electron flux on a volume basis: a new approach to the analysis of Fast Repetition Rate fluorometry (FRRf) data. Limnology and Oceanography: Methods 10: 142-154.

Oxborough K, Baker NR (2000) An evaluation of the potential triggers of photoinactivation of photosystem II in the context of a Stern–Volmer model for downregulation and the reversible radical pair equilibrium model. Philosophical Transactions of the Royal Society B 355: 1489-1498.

Oxborough K, Baker NR (1997) Resolving chlorophyll a fluorescence images of photosynthetic efficiency into photochemical and non-photochemical components - calculation of qP and Fv'/Fm' without measuring Fo'. Photosynthesis Research 54: 135-142.

Nina SCHUBACK

Hippmann AA, Schuback N, Moon KM, McCrow JP, Allen AE, Foster LJ, Green BR, Maldonado MT (2017) Contrasting effects of copper limitation on the photosynthetic apparatus in two strains of the open ocean diatom Thalassiosira oceanica. PLoS One 12: e0181753.

Hoppe CJM, Schuback N, Semeniuk D, Giesbrecht K, Mol J, Thomas H, Maldonado MT, Rost B, Varela DE, Tortell PD (2017) Resistance of Arctic phytoplankton to ocean acidification and enhanced irradiance. Polar Biology 3: 399–413.

Schuback N, Hoppe CJM, Trembley JE, Maldonado MT, Tortell PD (2017) Primary productivity and the coupling of photosynthetic electron transport and carbon fixation in the Arctic Ocean. Limnology and Oceanography 62: 898–921.

Schuback N, Flecken M, Maldonado MT, Tortell PD (2016) Diurnal Variation in the Coupling of Photosynthetic Electron Transport and CO2-assimilation in Iron-limited Phytoplankton in the NE subarctic Pacific. Biogeosciences 13: 1019–1035.

Schuback N, Schallenberg C, Duckham C, Maldonado MT, Tortell PD (2015) Interacting effects of light and Iron availability on the coupling of photosynthetic electron transport and CO_2-assimilation in marine phytoplankton. PLoS One 10: e0133235.

David SUGGETT

Hughes DJ, Varkey D, Doblin MA, Ingleton T, Mcinnes A, Ralph PJ, van Dongen-Vogels V, Suggett DJ (2018). Impact of nitrogen availability upon the electron requirement for carbon fixation in Australian coastal phytoplankton communities. Limnology and Oceanography. In Press.

Zhu Y, Ishizaka J, Tripathy S, Wang S, Sukigara C, Goes J, Matsuno T, Suggett DJ (2017) Relationship between light, community composition and the electron requirement for carbon fixation in natural phytoplankton. Marine Ecology Progress Series 580: 83-100.

Suggett DJ, Goyen S, Evenhuis C, Szabó M, Pettay DT, Warner ME, Ralph PJ (2015) Functional diversity of photobiological traits within the genus Symbiodinium appears to be governed by the interaction of cell size with cladal designation. New Phytologist 208:370–381

Suggett DJ, MacIntyre HL, Kana TM, Geider RJ (2009) Comparing electron transport with gas exchange: Parameterising exchange rates between alternative photosynthetic currencies for eukaryotic phytoplankton. Aquatic Microbial Ecology 56: 147-162.

Suggett DJ, Moore CM, Hickman AE, Geider RJ (2009) Interpretation of Fast Repetition Rate (FRR) fluorescence: Signatures of phytoplankton community structure versus physiological state. Marine Ecology Progress Series 376: 1-19.

Sandy THOMALLA

Ryan-Keogh T, Thomalla SJ, Little H, Melanson JR (2018) Seasonal regulation of the coupling between photosynthetic electron transport and carbon fixation in the Southern Ocean. Limnology and Oceanography. In Press.

Thomalla SJ, Moutier W, Ryan-Keogh T, Schutt J (2017) An optimised method for correcting fluorescence quenching using optical backscattering on autonomous platforms. Limnology & Oceanography: Methods 16: 132-144.

Ryan-Keogh T, Thomalla SJ, Mtshali T, Little H (2017) Modelled estimates of spatial variability of iron stress in the Atlantic sector of the Southern Ocean. Biogeosciences 14: 3883-3897.

Thomalla SJ, Kean E, Gibberd M-J, Lucas M, Barlow R (2017) Photosynthesis versus irradiance relationships in the Atlantic sector of the Southern Ocean. African Journal of Marine Science 39: 43-57.

Thomalla SJ, Ogunkoya G, Vichi M, Swart S (2017) Using optical sensors on gliders to estimate phytoplankton carbon concentrations and chlorophyll-to-carbon ratios in the Southern Ocean. Frontiers in Marine Science 4: 34.

Philippe TORTELL

Burt WJ, Westberry TK, Behrenfeld MJ, Zeng C, Izett R, Tortell PD (2018). Carbon: Chlorophyll ratios and net primary productivity of subarctic Pacific surface waters derived from autonomous shipboard sensors. Global Biogeochemical Cycles. 10.1002/2017GB005783.

Izett RW, Manning CC, Hamme RC, Tortell PD (2018) Refined estimates of net community production in the Subarctic Northeast Pacific derived from $\Delta O_2/Ar$ measurements with N_2O-based corrections for vertical mixing. Global Biogeochemical Cycles doi:10.1002/2017GB005792

Schuback N, Hoppe CJM, Trembley JE, Maldonado MT, Tortell PD (2017) Primary productivity and the coupling of photosynthetic electron transport and carbon fixation in the Arctic Ocean. Limnology and Oceanography 62: 898–921.

Goldman JA, Kranz SA, Young JN, Tortell PD, Stanley RH, Bender ML, Morel FM (2015) Gross and net production during the spring bloom along the Western Antarctic Peninsula. New Phytologist 205: 182-91.

Tortell PD, Asher EC, Ducklow HW, Goldman JAL, Dacey JWH, Grzymski JJ, Young JN, Kranz SA, Bernard KS, Morel FMM (2014) Metabolic balance of coastal Antarctic waters revealed by autonomous pCO_2 and $\Delta O_2/Ar$ measurements Geophysical Research Letters. 41: 6803-6810.