MSc Program
Environmental Technology & International Affairs

Regulation Under Scientific Uncertainty: Effectiveness, Impacts and Governance of Ocean Iron Fertilization

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Vienna, 03.06.2013

Affidavit

I, **PATRICK AUREL TOUSSAINT**, hereby declare

1. that I am the sole author of the present Master's Thesis, "REGULATION UNDER SCIENTIFIC UNCERTAINTY: EFFECTIVENESS, IMPACTS AND GOVERNANCE OF OCEAN IRON FERTILIZATION", 68 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Abstract

The geoengineering technique of ocean iron fertilization (OIF) has been proposed as a Plan B to complement current mitigation efforts to stabilize global average temperature increase at a non-dangerous level. However the technique has been criticized for its low effectiveness and the possibility that it may create adverse environmental impacts when applied at a larger scale. Due to the scientific uncertainty pervading both climate change impacts and the potential environmental risks of OIF, regulators are thus faced with an improbable balancing exercise. The international community has responded to this challenge through the adoption of a *de facto* moratorium on such activities; a response which may be overly restrictive, yet ineffective. While some in the scientific community advocate further, legitimate research into the technology, a recent unsanctioned OIF experiment has shown that unilateral deployment of the technology remains largely unregulated.

This thesis provides an analysis of the processes, effectiveness and environmental impacts of OIF and identifies a set of key governance challenges unique to the technology. Based on these governance challenges, the thesis examines the suitability of existing international regulatory mechanisms that apply to OIF and exposes the gaps remaining in the regulation of such activities. On the basis of this comprehensive scientific and legal analysis a set of recommendations is formulated which aim to strengthen the existing regulatory framework and contribute to future governance of the technology.

Acknowledgements

”Geoengineering is like a junkie figuring out
new ways of stealing from his children”
– Meinrat Andreae

First and foremost, I wish to thank my parents for the amazing yet improbable opportunity of pursuing a second master’s degree. Their continued support throughout my six years of study has been infallible and one should think I have now specialized enough.

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Much of the preparatory work and writing of this thesis took place in Nairobi, during the rainy season. It would not have been possible without the love and care of Priscilla whose kind words of encouragement have been a constant reminder of what is important in life.

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List of Abbreviations/Acronyms

BAU	Business as usual
CBD	United Nations Convention on Biodiversity 1992
CDR	Carbon dioxide removal
Chl α	Chlorophyll alpha
CO_2e	Carbon dioxide equivalent
COP	Conference of the Parties
DIC	Dissolved inorganic carbon
DOC	Dissolved organic carbon
EEZ	Exclusive economic zone
EIA	Environmental impact assessment
GE	Geoengineering
GHG	Greenhouse gas
GWP	Global warming potential
HAB	Harmful algal bloom
HNLC	High-nutrient, low-chlorophyll regions
HSRC	Haida Salmon Restoration Council
ICJ	International Court of Justice
IFE	Iron fertilization efficiency
IL	International law
IPCC	Intergovernmental Panel on Climate Change
KP	Kyoto Protocol 1997
LC/LP	London Convention and Protocol

LICG	Legal and Intersessional Correspondence Group on Ocean Fertilization
MLH	Mixing layer height
OIF	Ocean iron fertilization
POC	Particulate organic carbon
POM	Particulate organic matter
SBSTTA	Subsidiary Body on Technical and Technological Advice
SRM	Solar radiation management
UNCLOS	United Nations Convention on the Law of the Sea 1982
UNCSD	Rio+20 United Nations Conference on Sustainable Development 2012
UNEP	United Nations Environment Programme
UNESCO-IOC	International Oceanographic Commission
UNFCCC	United Nations Framework Conference on Climate Change 1992
UNGA	United Nations General Assembly
VCLT	Vienna Convention on the Law of Treaties 1969

1. Introduction

In July 2012, Russ George, an American entrepreneur conducted an unapproved ocean iron fertilization experiment dumping 120 tons of iron sulphate into the Pacific Ocean. Dubbed a “rogue geoengineer” by environmental protection groups (Lukacs, 2012c), Mr. George’s actions raise the question to what extent manipulations of the marine environment with the intent of counteracting global warming – short, marine-based geoengineering methods – fall under international regulation.

There has been a recent surge in literature on geoengineering in what concerns both impacts and governance of such techniques. This surge can be attributed to the increased salience of alternative responses to climate change given that current efforts to limit or reduce anthropogenic greenhouse gas emissions are falling far short of the level required to stabilize global average temperature increase (IPCC, 2007; UNEP, 2012). Geoengineering more broadly raises a plethora of questions ranging from how we should deal with scientific uncertainty to the social and ethical acceptability of tampering with the Earth’s climate. Since the concept of geoengineering has only recently gained traction, many studies concerning its governance and regulation provide an overview of the whole spectrum of land-based and ocean-based techniques. For the purposes of this thesis, however, we shall focus exclusively on ocean iron fertilization (OIF), considered to be the most thoroughly studied geoengineering technique to date.

1.1. Background on Geoengineering

Geoengineering (GE) or more specifically ‘climate engineering’ implies the large-scale modification of the climate system with the aim of counteracting anthropogenic climate change (Royal Society, 2009). Since GE involves a deliberate intervention with effects on the global climate it needs to be distinguished from weather modification, which has been around much longer as a concept. Geoengineering has been dubbed a ‘Plan B’ to solve the problem of global warming in reference to the fact that current global efforts at mitigating greenhouse gases (GHGs) are failing to stabilize global average temperature at 2ºC – a threshold considered safe to prevent adverse impacts from further warming. There are two broad categories of geoengineering, classifying technologies either as solar radiation management

(SRM) or carbon dioxide removal (CDR) techniques (Royal Society, 2009). While SRM techniques involve an alteration of the planet's albedo, for example by stimulating marine cloud formation or injecting reflective aerosols into the stratosphere, CDR techniques work by removal and subsequent storage of CO_2 in a carbon sink where it remains sequestered. The various geoengineering methods differ greatly in terms of their effectiveness, safety and readiness and there has been substantial public debate about the desirability of their deployment. One of the key points contended is that some techniques may lead to adverse environmental impacts that outweigh their potential benefit of reducing global warming.

1.2. The challenge of regulating under scientific uncertainty

The state of research into the environmental and knock-on impacts of geoengineering techniques on the climate system is characterized by a large degree of uncertainty: in many cases, impacts are speculative and their reversibility unknown (CBD SBSTTA, 2012). This presents a tough challenge for regulators when trying to decide between pursuing a particular geoengineering method and facing the environmental impacts of poorly mitigated climate change. Climate impacts themselves are subject to another kind of uncertainty; although we know from the IPCC's seminal Fourth Assessment Report (IPCC, 2007) what types of adverse effects may result from global warming, we cannot fully predict when and where they will occur and at what frequency. It comes to no surprise then that State Parties to the two main international agreements relevant to marine-based geoengineering have enacted a moratorium on such activities (to be discussed in more detail in the legal analysis). As has been argued elsewhere (Toussaint, 2012), given the threat of uncertain impacts and the challenge of taking the right level of precaution, such a restrictive regulatory response aiming to limit the GE activity may indeed appear justified. The findings presented in this thesis will determine to what extent this assumption holds true in the case of ocean iron fertilization.

1.3. Why focus on Ocean Iron Fertilization?

A comprehensive assessment that encompasses the whole range of land- and ocean-based SRM and CDR techniques would excessively broaden the scope of the thesis and make an effective analysis of geoengineering methods and their regulation impossible. The thesis therefore focuses on the field of marine-based methods of geoengineering, limiting its analysis to the method of ocean iron fertilization. The choice of focusing on this ocean-based GE method is justified on the basis that among the entire range of geoengineering techniques it is the most advanced in terms of research on its feasibility, effectiveness and environmental impacts (Royal Society, 2009) and it is the only technique that has been subject to a significant number of field experiments. Other marine GE methods such as the enhancement of marine cloud albedo, enhanced upwelling and ocean fertilization via the addition of macronutrients nitrogen or phosphorus are thus excluded from this analysis[1].

1.4. Hypothesis

The scientific uncertainty underlying the research and large-scale deployment of OIF poses significant challenges for the international regulation of such activities. Through a thorough analysis of the processes, effectiveness and environmental impacts of OIF, a set of governance challenges is identified. On the basis of these governance challenges, the thesis examines the suitability of existing international regulatory mechanisms applicable to OIF and makes relevant recommendations for future governance of the technology.

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[1] For detailed analysis of other marine-based geoengineering methods, their effectiveness and their environmental impacts, see CBD SBSTTA (2012) Impacts of Climate-related Geoengineering on Biological Diversity, UNEP/CBD/SBSTTA/16/INF/28.

2. Scientific Analysis

This section provides a literature review and analysis of the science behind ocean iron fertilization (OIF). The section begins with an explanation of the biogeochemical processes involved in OIF, and subsequently provides a detailed analysis of its effectiveness and environmental impacts. Furthermore, it highlights the difficulties of monitoring and verification of field trials and deployment and provides an assessment of the costs of the technology as well as an examination of whether it is possible to generate emission reduction credits. In closing this section we translate these findings into specific governance challenges that must be addressed by regulation.

2.1. Ocean Iron Fertilization – how it works

In 1990 John Martin posited the 'iron hypothesis' suggesting that by adding 1 ton of iron to the oceans 30,000 to 100,000 tons of carbon could be sequestered from the atmosphere (Martin, 1990: 2; Sunda et al., 1991). Efficiency estimates have become more accurate over the past two decades, yet the fundamental idea behind OIF remains the same. It is a process whereby iron, commonly in the form of ferrous sulphate ($FeSO_4$) is injected from a ship vessel into a patch in the surface layer of the ocean – the sunlit or euphotic zone – in a region that is originally deficient in iron (Fe). This Fe addition stimulates the growth of a phytoplankton bloom, which through the high availability of macronutrients – nitrogen (N) and phosphorus (P) – in the water generates high levels of primary production via photosynthesis, converting CO_2 and sunlight into oxygen and organic carbon (Figure 1). In doing so, OIF aims to enhance the biological uptake of CO_2 from the atmosphere, a natural process known as the 'biological pump', which forms an essential part of the marine carbon cycle.

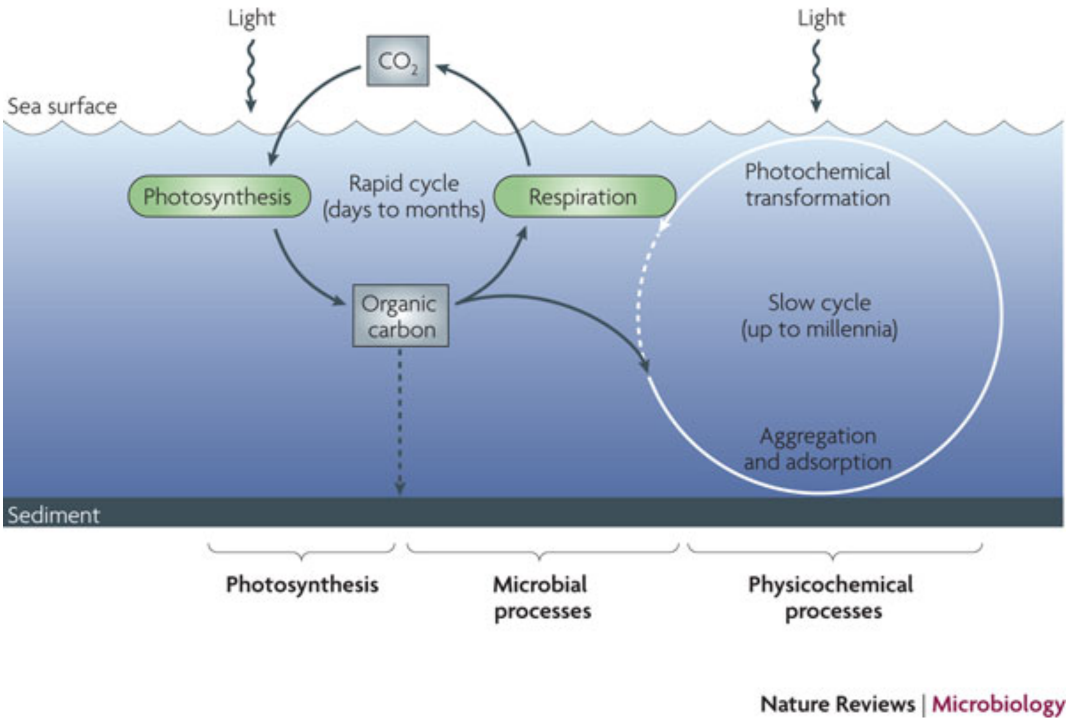

Figure 1: Marine Carbon Cycle. Source: Jiao et al., 2010: 596

2.1.1. Marine carbon cycle

The marine carbon cycle works through a series of physical and biological processes, known as air-sea exchange of CO_2, the ‘physical pump’ and the ‘biological pump’.

During air-sea gas exchange, atmospheric CO_2 reacts with seawater to form bicarbonate (HCO_3-) or dissolved inorganic carbon (DIC) and thereby becomes available for photosynthesis. Phytoplankton photosynthesizes DIC, converting it into biologically available or ‘organic’ carbon. This lowers the concentration of DIC in the euphotic zone and leads to an undersaturation vis-à-vis atmospheric concentrations of CO_2. The resulting partial pressure stimulates increased uptake of CO_2 from the atmosphere (Lampitt et al., 2008).

The physical carbon pump – or solubility pump – is a key process determining air-sea exchange of CO_2. Physical mixing of ocean waters transports warmer waters from low latitude regions towards high latitude regions thereby cooling it. This is important since atmospheric CO_2 has a higher solubility in colder seawater and as a result the vertical mixing induced by the physical carbon pump enhances the ocean's capacity to take up atmospheric carbon as DIC. The CO_2-enriched cooled seawater has a higher density and sinks below the surface layer thereby subducting nutrients and carbon dioxide into deep water circulation that essentially removes them from contact with the atmosphere for hundreds of years – this process is known as vertical mixing. By reverse, as cold seawater resurfaces it is warmed up again and releases carbon dioxide to the atmosphere[2].

The biological pump is a pathway by which atmospheric carbon is incorporated into living organisms in the surface layer of the ocean and transferred into the deep-water layers via physical processes. As organic matter decomposes, microbial respiration in the surface layer and mid-water converts organic carbon back into CO_2. Further, the organic carbon produced by photosynthetic primary production is repackaged through various food web processes forming an aggregate known as 'marine snow' (Cullen and Boyd, 2008: 297). This aggregate particulate organic matter (POM) consists mainly of dead phytoplankton resulting from nutrient depletion during the decline of a bloom and fecal matter produced by zooplankton after it has fed on phytoplankton (Buesseler, 2012). Part of this POM sinks due to gravitational settling below the euphotic zone (below 100 m), thereby inducing a downward flux of particulate organic carbon (POC) commonly referred to as POC export. Studies have demonstrated that POC export decreases with depth due increased decomposition by microbes and zooplankton grazing (Cullen and Boyd, 2008: 297). Therefore only a small portion of POC reaches the deep-water layer where it stays out of the contact with the atmosphere for over 100 years and can be considered sequestered (Cullen and Boyd, 2008). A fraction of this portion eventually sediments and becomes buried in the ocean ground.

2.1.2. Nutrient availability

Ocean iron fertilization and, by extension, the activity of the biological pump depend largely on the availability of nutrients required by phytoplankton for metabolic processes and thus for photosynthesis. These include macronutrients such as N and P and micronutrients such as iron (Fe) and in certain cases silicate (Si). Fe in

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[2] For more detailed information on the marine carbon cycle and its processes, see Berner and Berner, 2012 – Chapter 1: Introduction to the Global Environment: The Water and Energy Cycles and Atmospheric and Oceanic Circulation, pp. 1-23.
Available online at http://press.princeton.edu/chapters/s9772.pdf [accessed 27/04/2013]

particular is used both in photosynthesis and nitrate (NO_3) reduction, both are essential to phytoplankton growth (Gnanadesikan and Marinov, 2008). In fact, phytoplankton growth is subject to various limiting factors, first and foremost temperature, light and nutrient availability. The global oceans have varying levels of macro- and micronutrient concentrations and in a number of field experiments it has been determined that OIF is only effective in regions that have high macronutrient levels, so-called High Nutrient Low Chlorophyll (HNLC) regions, which cover around 20% of the world oceans (Pitchford and Brindley, 1999; Figure 2). This is because these regions are typically low in natural Fe and iron acts as a limiting nutrient inhibiting phytoplankton growth (Martin, 1990). Once Fe is added, unused or 'preformed' macronutrients become part of the biologically utilized pool and increase the ocean's capacity to hold carbon (Gnanadesikan and Marinov, 2008). Martin's iron hypothesis rests on an observed C:Fe ratio known in ocean biogeochemistry as the Redfield ratio.

The Redfield ratio provides a useful measure to determine the amount of carbon exported from the surface layer as macronutrients are depleted through the bloom. It sets out the ratio of nutrient atoms to carbon atoms, typically in the order of C:N:P (106:16:1) (below the euphotic zone[3]). The ratio becomes important when considering the effectiveness and environmental impacts of OIF which may alter nutrient concentrations and as a result alter the Redfield ratio. It must be noted, however, that the nutrient stoichiometry may naturally vary due to differences in surface ocean nutrient supply (Guieu et al., 2009; Figure 2).

A final important factor to be considered when discussing nutrient availability is the concept of co-limitation. This rests on the assumption that a low concentration of one nutrient needed for phytoplankton growth and primary production may render the phytoplankton community more vulnerable to limitation by another nutrient (Lampitt et al., 2008). Importantly, phosphorus is often considered the 'ultimate limiting nutrient' given its scarce availability and lack of alternative supply, whereas nitrogen is on average depleted more quickly (Tyrrell, 1999). Sunda and Huntsman (1997) suggest that HNLC regions are characterized by co-limitation of Fe and light.

[3] Though it has been estimated that the nutrient ratio of particulate matter in surface water does not deviate greatly from the standard Redfield ratio (Chen 1996 in Lampitt et al., 2008).

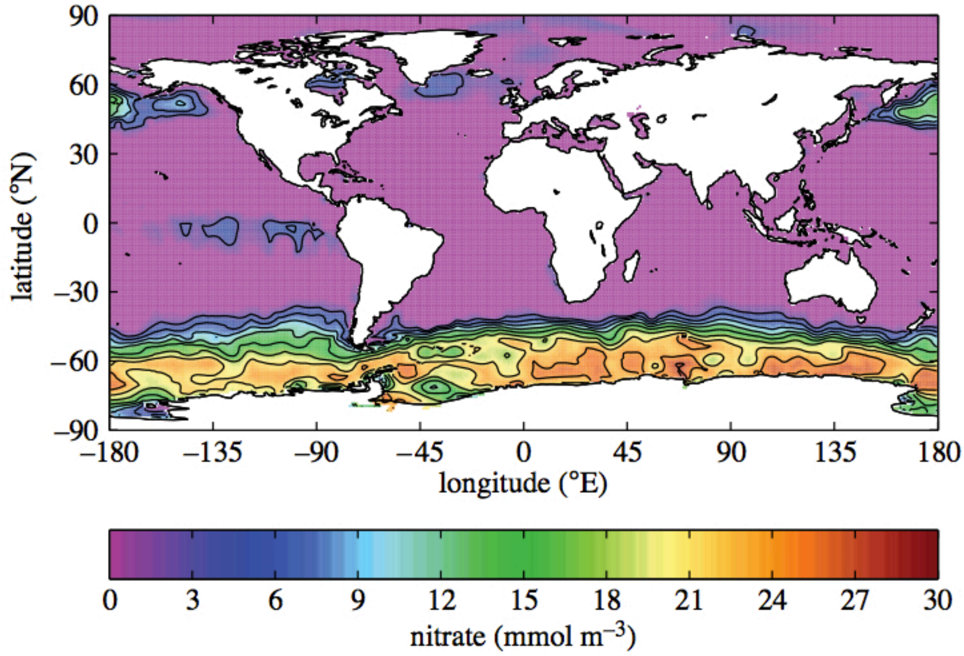

Figure 2: Global annual minimum distribution of surface concentrations of nitrate, one of the principal macronutrients limiting primary production (Levitus World Ocean Atlas 1994, reproduced in Lampitt et al., 2008)

2.1.3. Conversion factors

The degree of conversion of surface layer DIC into organic carbon is determined by a number of natural factors specific to the geographic region where the phytoplankton bloom occurs. First and foremost, light limitation is said to be the ultimate determinant of phytoplankton growth (De Baar et al., 2005: 10). Not only does the amount of incident light – or photosynthetically active radiation – tend to vary on diurnal and seasonal basis (2005: 10), it is also affected by the mixing layer height (MLH). The MLH describes the depth of lateral and vertical mixing of the fertilized patch and underlying waters. It depends on the vertical temperature gradient and wind stress at the interface between water and atmosphere, which significantly dilutes the original patch size and therefore affecting both nutrient and carbon concentrations (2005: 11) and the degree of phytoplankton accumulation required for a bloom (Law et al., 2011). In their comparison of eight OIF experiments conducted between 1993 and 2004, De Baar et al. conclude that the deeper the MLH, the lower the maximum Chlorophyll α yield (an indicator of phytoplankton growth) and the lower the removal of DIC from the surface layer (2005: 10). In the Southern Ocean, light conditions determined by wind velocity and mixing are only suitable for phytoplankton growth during the austral summer months (Dec-Jan); this favorable period increases to the north from about three months off the Antarctic Coast to about six months north of the Polar Front (Aumont and Bopp, 2006: 8).

2.1.4. Spatial and temporal scales

Moreover, it is important to consider the spatial and temporal scales involved in OIF. When iron addition successfully results in a phytoplankton bloom, such a bloom commonly lasts a few weeks or months (De Baar et al., 2005; Boyd et al., 2007). By comparison, the process of POC export can continue well after the bloom has collapsed. Most OIF field experiments conducted to date (thirteen excluding the 2012 attempt by Russ George) have carried out small-scale patch fertilizations over an ocean area no larger than 100 km^2 and monitoring rarely lasted longer than the actual duration of the bloom and its decline (max. two months with largest research vessel (Watson et al., 2008: 303). This is because during the peak of austral summer (Dec-Jan), the season with the most favorable light conditions for OIF it is reportedly difficult to secure ship-time (Monterey & Levitus 1997 in De Baar et al., 2005). Further, the use of sulphur hexafluoride (SF6) tracers to monitor the bloom is impractical over larger spatial scales since it has a relatively short residence time in the surface water (Watson et al., 2008: 307). Lastly, while remineralization of organic carbon is very fast (days; Boyd et al., 2004), ocean carbon sequestration potentials of OIF are modeled over annual, 10-year and 100-year periods.

2.2. Effectiveness

In its 2009 reference report on geoengineering, the Royal Society evaluated ocean fertilization as a method "likely to be feasible but not very effective" (2009: 18). This stands in stark contrast to the high C:Fe ratio[4] suggested in Martin's Iron Hypothesis. In this section we shall determine to what extent this statement holds true and provide an explanation of the factors likely to affect the technique's effectiveness. In order to evaluate the CO_2 sequestration potential and the suitability of OIF as a CO_2 mitigation strategy, we first must consider two fundamental measures: the efficiency of atmospheric carbon uptake and carbon export efficiency. Subsequently, we shall

[4] The C:Fe ratio is also known as the Iron Fertilization Efficiency (IFE) (Lampitt et al., 2008).

compare the CO_2 sequestration potential with natural ocean iron fertilization and global annual CO_2 emissions alongside current reduction pledges.

2.2.1. Atmospheric uptake efficiency

The atmospheric uptake efficiency refers to the proportion of additional carbon export induced by OIF that is resupplied from atmospheric CO_2 (Williamson et al., 2012). High uptake efficiencies have been reported for the upper part of the euphotic zone where the conversion of DIC to organic carbon and subsequent POC export happen relatively close to the air-sea surface (Jin et al., 2008). By this logic, OIF near surface waters leading to a shallow bloom and shallow distribution of export production also leads to higher atmospheric uptake efficiencies (2008: 400). By contrast, uptake efficiency is lower at the bottom of the euphotic zone since the DIC pool tends to be replenished with DIC from surrounding waters rather than from atmospheric uptake. Williamson et al. indicate that models estimate a possible uptake efficiency of 70-90% for tropical waters while field studies suggest a much lower efficiency of 2-20% (2012). They argue this vast discrepancy may be due to short observation time during field trials where CO_2 uptake is likely to occur well beyond the weeks to months of vessel-based observation. De Baar et al. further explain that replenishment of CO_2 through air-sea exchange is slow (lasting several months up to one year; Sarmiento & Gruber 2006 in Jin et al., 2008: 390; Broecker & Peng 1982 in Watson et al., 2008: 305) and therefore continues much longer than most small-scale OIF field experiments (2005: 18). They also estimate that as a result of this long equilibration period, atmospheric CO_2 flux into the sea amounts to just 8% (2.7% - 13%) of DIC removed from the surface layer. Moreover, Jin et al. argue that the atmospheric uptake efficiency depends on size of the fertilized area rather than on the duration of fertilization and needs to be adjusted for atmospheric variability which is likely to reduce efficiency by 20% over ten years fertilization and 50% over 100 years (2008: 395).

To provide a direct comparison with the 1:30,000-100,000 C:Fe ratio from Martin's Iron Hypothesis, the highest Iron Fertilization Efficiency (IFE) achieved during the 1993-2004 era of OIF experiments was SEEDS[5] conducted in 2001 in the northwest Pacific Ocean. In SEEDS, a single injection of $FeSO_4$ at optimal conditions reportedly achieved a maximum C:Fe efficiency of 15,000 (11,800 after adjustment

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[5] Subarctic Pacific Iron Experiment for Ecosystem Dynamics Study (SEEDS)

to account for WML depth) during the early bloom stages at a DIC removal rate of 88% of primary production (De Baar et al., 2005: 20). This is set against an average IFE (C:Fe) of 5600 among all eight OIF experiments between 1993-2004 evaluated in the study. However, this figure is even smaller when we consider POC export in subsection 2.2.2 below.

Atmospheric uptake efficiency depends primarily on the rate of air-sea exchange of CO_2, which is determined by the partial pressure gradient of CO_2 between the atmosphere and seawater. Air-sea gas exchange is further influenced by physical factors such as wind and waves and the remineralization rate of exported POC (Williamson et al., 2012). The atmospheric uptake efficiency is also limited by the fraction of carbon export resupplied by the marine mixing processes, the extent of which is determined through yet another set of factors. De Baar et al. (2005) add to this list the extent of lateral dilution, sea surface irradiance, temperature and zooplankton grazing. For example, they report that a during a bloom, highly abundant phytoplankton reduces incident light for algal organisms below, decreasing maximum potential phytoplankton growth – a phenomenon known as 'self-shading' (2005: 10).

2.2.2. Carbon export efficiency

The carbon export efficiency is expressed as the fraction of POC of primary production which is exported below the euphotic zone into deep water below 100m. Crucially, it is assumed that only 18-26% of primary production by phytoplankton is converted to POC due to grazing and other food web losses (De Baar et al., 2005: 19). It has further been suggested that POC production is thereby enhanced only for the upper 20m while POC remineralization occurs down to 200m depth, leading to a negative net community production (Jin et al., 2008: 397; Figure 3).

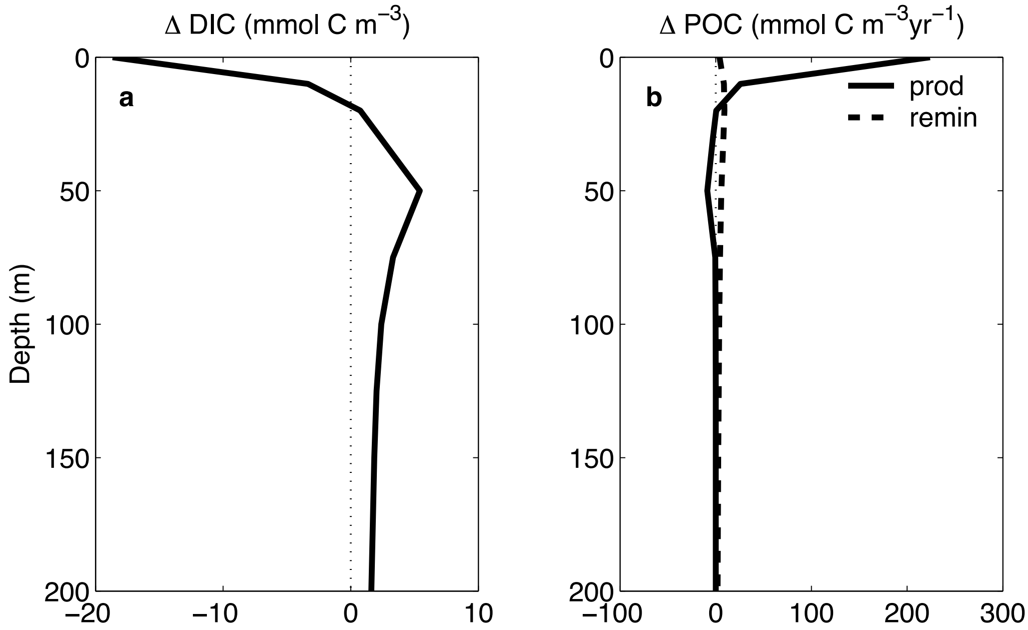

Figure 3: Vertical profiles of anomalous properties averaged over the eastern tropical Pacific analysis region (101.6 W to 112.4 W and 8.5 S to 0.6 N) for the STANDARD case. Source: Jin et al., 2008: 397

Referring to the period between 1993 and 2005 Boyd et al. (2007) indicate that of eleven OIF experiments which observed POC export, only five reported an increase while the remainder reported no change. As a rule of thumb, Powell et al. reason POC export efficiency decreases with depth, 5-50% remineralizes before sinking to 100m depth, while only 2-25% sinks between 100 and 500m (2008: 11). Jin et al. estimate the POC export efficiency in their model at approximately 10% despite substantial shallow remineralization of organic carbon (2008: 392). Harrison provides the most recent data covering previous review studies of OIF experiments (including De Baar et al. 2005) and suggests a range of POC export efficiency from 0% and 50%, with a 9.3% average POC flux taken as the most probable estimate (2013: 14). The highest observed POC export in an OIF experiment is 50% during EIFEX (2004)[6], roughly five times the export flux reported for any other OIF experiment. For reference, Harrison provides a summary of POC export efficiencies (including figures from De Baar et al., 2005) which has been incorporated in Table 1.

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[6] European Iron Fertilization Experiment (EIFEX); This high value should be treated with caution since EIFEX was both unique in its hydrographic characteristics and favorable weather conditions, as the iron was injected into the core of an eddy.

Table 1: Selection of carbon export measurements. Source: Harrison, 2013: 7, adapted from Smetacek et al., 2012

Reference	*Experiment*	*Location*	*Measurement depth*	*Measured value*	*Export flux estimated at 250 m*
de Baar et al. (2005)	SOIREE	S. Ocean	100 m	Negligible	0
Smetacek (2001)	EisenEx	S. Ocean	Unknown	0	0
Mazzocchi et al. (2009)	LOAHFEX	S. Ocean	Unknown	0	0
Harvey et al. (2010)	SAGE	S. Ocean	Unknown	0	0
de Baar et al. (2005)	SERIES	N. Pacific	120 m	3%	1.6%
de Baar et al. (2005)	SEEDS	N. Pacific	40 m	12%	2.5%
de Baar et al. (2005)	SOFEX-S	S. Ocean	100 m	12%	5.5%
de Baar et al. (2005)	IronEx II	Eq. Pacific	25–40 m	10%–27%	1.4%–5.6%
Smetacek et al. (2012)	EIFEX	S. Ocean	100 m	50%	50%*
Average patch					*6.66%*
Aufdenkampe et al. (2001)		Eq. Pacific	1% light level	16% nominal average	7.3%
Blain et al. (2007)		S. Ocean	100	30%	13.7%
Buesseler et al. (1992)	JGOFS	N. Atlantic	35 m	2%–42%	0.4%–7.8%
Buesseler et al. (2003)	AESOPS	S. Ocean	100 m	15%–65%	6.8%–29.6%
Doney (1999)	OCMIP-2 model	Global	Modelled @ 75 m	33%	11.2%
Brix et al. (2006)		N. Atlantic	150 m	6%	3.9%
Brix et al. (2006)		Pacific	150 m	6%	3.9%
Average broad system					*9.4%*

Notes: Divided into experimental patch scale measurements and measurements of broad natural systems. *During the EIFEX experiment it appears that remineralisation of the sinking organic matter did not follow the Martin remineralisation curve.

In comparison with Martin's iron hypothesis C:Fe ratio, De Baar et al. estimate POC export into deep water to lie between 650 to 25,000 $C:Fe_{exported}$ (2008). They posit that the range in POC export efficiency is due to significant variability in ocean conditions before each iron addition (factors include phytoplankton abundance and taxonomy, zooplankton, water column stratification and temperature) and weather conditions after addition (light availability and wind affecting mixing depths) (2008:

280). This variability leads to significant uncertainties in understanding POC export and makes it difficult to provide a general estimate of its efficiency. De Baar et al. posit that this variability and the dilution of the patch initially fertilized mean that complete comparability between experiments may never be achieved (2005: 17).

2.2.3. CO_2 sequestration potential

There is little actual data on the CO_2 sequestration potential that has been acquired through small-scale field experiments. In fact, of the thirteen artificial OIF experiments carried out to date, not all were designed to measure carbon export from the upper ocean and none were designed to measure CO_2 sequestration[7]. This is because of the long time-scales (centuries) involved in marine carbon sequestration and the difficulty of measuring carbon storage. Most estimates derived are from models and must be distinguished according to short-term (10 years) and long-term (100 years) application of OIF. Modeling studies focused on different geographic locations, with different weather conditions, over different patch sizes and time-scales, leading to diversity in estimates.

The amount of carbon sequestered roughly equals the difference between the net air-sea flux of CO_2 due to OIF and that which would have occurred in its absence and cannot be calculated by simple means (Watson et al., 2008: 305). However, it can be derived when combining atmospheric uptake efficiency and carbon export efficiency. Recent estimates by Williamson et al. (2012) suggest that using the highest estimates for both uptake and export efficiency, a global-scale application of OIF could sequester at maximum 25-75 Gt C over 100 years (relying on data from Aumont & Bopp, 2006 and Zahariev et al., 2008), with the highest potential in the Southern Ocean. This corresponds with the author's own literature survey which yields a CO_2 sequestration potential for OIF in the range of 26-70 Gt C over 100 years (Aumont and Bopp, 2006; Jin et al., 2008; Lenton and Vaughan, 2009; Zahariev et al., 2008; Zeebe and Archer, 2005).

Central to determining the CO_2 sequestration potential of OIF is the question of whether and how long the carbon exported stays out of contact with the atmosphere. Sarmiento et al. observe that the back flux of CO_2 from the ocean to the atmosphere is substantial so that a realistic atmospheric carbon reservoir must be considered

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[7] Based on De Baar et al., 2005 (8 OIF experiments between 1993-2004) and Lampitt et al., 2008 (12 OIF experiments between 1993-2008).

when modeling CO_2 sequestration potential (2010). Specifically, their calculations show that after 100 years of continuous OIF application, 50% of the CO_2 absorbed in a model without atmospheric reservoir is lost back to the atmosphere in a model where a realistic reservoir is included. In case of a one-off Fe addition, the loss of CO_2 sequestered is in the order of 70% or greater (2010: 3619). The extent of this loss mechanism is dependent on the location where the carbon-enriched water resurfaces. Harrison points out that where the exported carbon and associated nutrients resurface within a HNLC region, new primary production is again iron-limited (2013: 8) or light-limited in the case of the Southern Ocean (Popova et al., 2000). However, if the CO_2 enriched water resurfaces outside a HNLC region, it is re-supplied by iron and the carbon is re-exported, thereby returning to being sequestered (2013: 8).

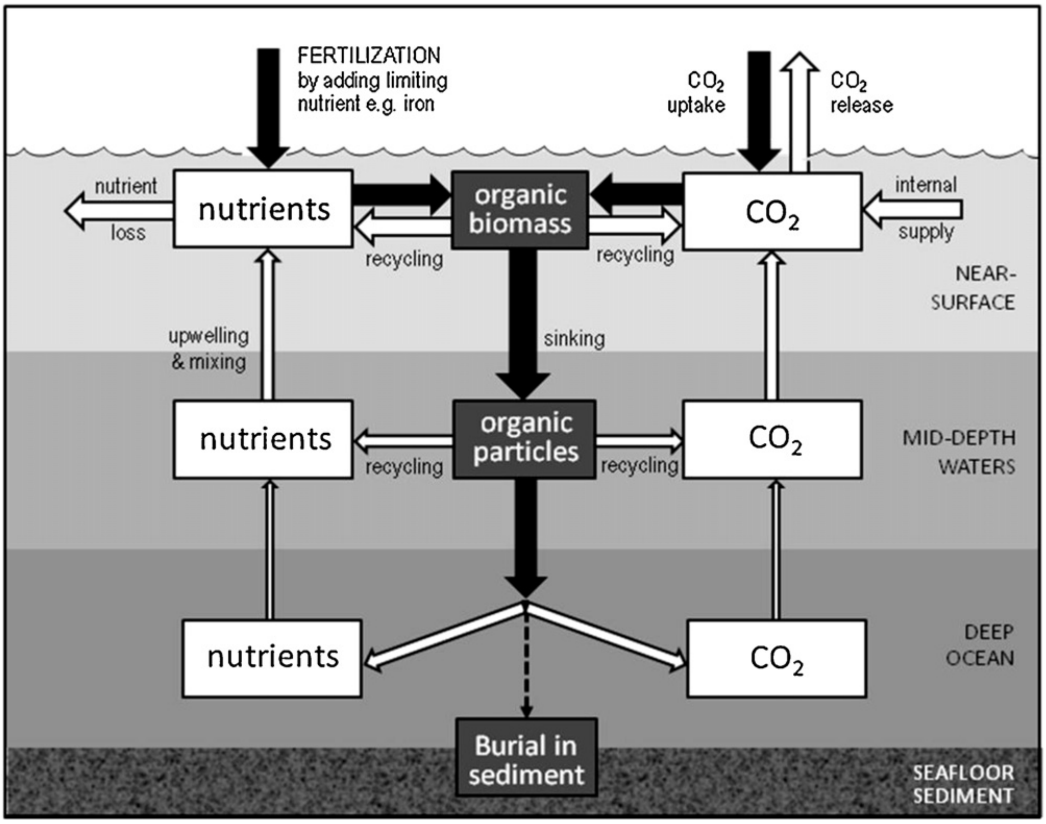

Figure 4: Processes affecting the carbon sequestration efficiency of large-scale ocean fertilization. The near-surface ocean is the sunlit, mixed layer (usually 50–200 m) that is able to rapidly exchange gases with the atmosphere, and where biological carbon fixation occurs. Processes in mid-depth waters (also known as the mesopelagic layer or twilight zone) affect the decomposition of exported organic carbon, and its return to the atmosphere on a timescale of years to decades. The deep ocean (below ~1 km) is characterized by stable temperatures and very slow circulation and mixing; carbon reaching that part of the ocean is isolated from the climate system on a timescale of centuries to millennia. Source: Williamson et al., 2012: 480

2.2.4. Comparison with natural iron fertilization

Natural ocean iron fertilization can result from iron containing soils being blown to sea by storms, melting of sea ice or icebergs, shallow shelf sediments, and river effluents (ACE CRC, 2008). To date there have been two seminal studies of this phenomenon, one over the Kerguelen plateau (Blain et al., 2007) and the other near the Crozet Islands (Pollard et al., 2009), both located in the Southern Ocean. Recalling the C:Fe ratio of 1:30,000-100,000 posited by Martin (1990) and by Sunda (1991), taken together these studies suggest that the carbon sequestration achieved by natural ocean fertilization is between 10-18 times higher than estimates from artificial OIF experiments illustrated above.

2.2.5. Comparison with global GHG emissions and mitigation pledges

A comparison of the estimated OIF CO_2 sequestration potential of 25-75 Gt C over 100 years (provided by Williamson et al.) with estimates of cumulative CO_2 emissions from fossil fuel burning in the order of 900-2000 Gt C by 2100 (from IPCC future emission scenarios), suggest that ocean fertilization could only achieve a relatively modest offset (less than 10%) of anthropogenic GHG emissions (2012: 479). To put this figure into perspective, the author has undertaken own calculations of the offset achieved via GHG emission reduction efforts currently pledged under international climate agreements, using data provided by the Emissions Gap Report 2012 (UNEP, 2012).

The data puts current global annual GHG emissions at 49 Gt CO_2e (or 13.4 Gt C) per year[8] and estimates that these emissions need to fall to 44 Gt CO_2e (or 12 Gt C) per year in 2020 in order to stabilize global average temperature increase at 2ºC. This means that current annual GHG emissions are approximately 11.36%[9] above the 2ºC limitation scenario, equaling an excess of 5 Gt CO_2e (or 1.4 Gt C)[10]. The Emissions Gap Report provides four emission reduction scenarios which include different combinations of conditional or unconditional country pledges under strict or lenient rules (See Figure 5). Under the most optimistic scenario by the year 2020, GHG emissions reductions by -6 Gt CO_2e (or -1.6 Gt C) can be achieved. This is set

[8] Median value with an uncertainty range of 45.6-54.6 Gt CO_2e (or 12.4-14.9 Gt C).
[9] Median value with an uncertainty range of 3.63%-24.09%.
[10] Median value with and uncertainty range of 1.6-10.6 GtCO2e (or 0.4-2.9 Gt C).

against a business-as-usual scenario (BAU) without any emission reduction pledges, amounting to global emissions of 58 Gt CO_2e (or 15.8 Gt C) in 2020.

The GHG mitigation potential of current emission reduction pledges as stipulated in the Report covers reductions over a ten-year period (2010-2020)[11], and amounts to -1.6 Gt C. Assuming constant annual emissions of 13.4 Gt C per year, this represents an offset of 1.2%. Given the same level of constant annual emissions during a 100-year application of OIF – and extrapolating the OIF CO_2 sequestration estimate range derived from our literature review to a ten-year period (-2.6 to -7.0 Gt C) – the offset produced by OIF would be in the range of 1.9% to 5.2%[12], which is minimally higher than that achieved given the strongest scenario of mitigation pledges presented in the 2012 Emissions Gap Report.

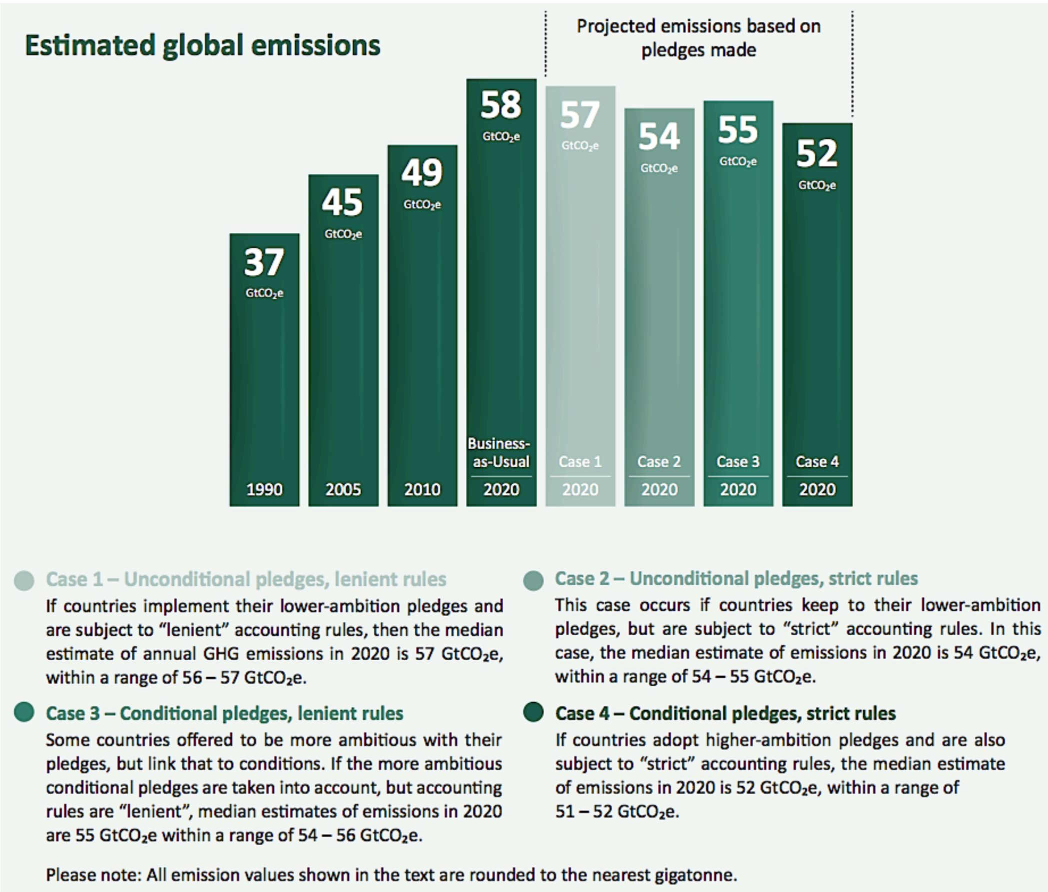

Figure 5: Estimated global emissions (historical, current, and projections under BAU and different emission reduction pledge scenarios) Source: UNEP Emissions Gap Report 2012

[11] To convert this reduction potential into an annual figure might be helpful for comparison with annual CO_2 reduction potential of OIF, but in reality emission pledges may not be implemented from year one, (if at all), and may not progress linearly.
[12] This corresponds with the <10% estimate provided by Williamson et al., 2012.

2.3. Environmental Impacts

This section analyzes the principal environmental impacts that may result from ocean iron fertilization. These include impacts which have been verified through small-scale field tests and those that are derived from models or inferred from studies of various ocean biogeochemical processes.

2.3.1. Ocean acidification

By enhancing the export of particulate organic carbon, OIF increases oxygen demand leading to oxygen depletion in mid-water and deep ocean (Cao and Caldeira, 2010). Hypoxic conditions can occur local to the fertilized patch or remotely, depending largely on circulation patterns. This could lead to an increase in so-called low oxygen regions (Williamson et al., 2012: 481); but not to completely anoxic conditions (Oschlies et al., 2010: 4026). Where upwelling waters are affected, OIF may result in an increase in frequency or extent of coastal hypoxia (Cullen and Boyd, 2008: 298). However, it is currently not possible to quantify the extent of oxygen depletion, primarily because models lack underlying data about preexisting oxygen distributions (Williamson et al., 2012: 481).

While much research has focused on the effect of complete anoxia, it has been shown that even prolonged exposure (>60 days) to hypoxic conditions negatively affects marine organisms, leading to higher levels of mortality (Knoll et al., 2007). The degree of exposure depends largely on circulation patterns but also on proximity to shallower shelf environments which tend to be highly productive and transport organic matter laterally over large distances (>100km) (Lampitt et al., 2008: 3930).

A crucial consequence of oxygen depletion is the modification of ocean pH. OIF is expected to increase pH in the euphotic zone due to increased photosynthetic activity, while decreasing pH to a small degree in deep-water (Lampitt et al., 2008: 3931), leading to deep ocean acidification (Cao and Caldeira, 2010). The potential impacts of ocean acidification on pelagic and benthic marine organisms are discussed in subsequent sections.

2.3.2. Changes to marine pelagic ecosystems

Where OIF successfully creates a phytoplankton bloom it leads to associated increases in primary productivity and phytoplankton biomass in the euphotic zone (Russell et al., 2012). This has been documented via remote sensing technology which recorded a 2-25-fold increase in chlorophyll α (Chl α) at the bloom location (Boyd et al., 2007). The response was greater where the bloom occurred in a shallower mixed layer (higher average light intensity) and was generally more rapid at higher temperature waters.

It has been demonstrated that relieving the iron limitation alters nutrient uptake rates and increases photosynthetic efficiency in phytoplankton (Behrenfeld et al., 1996) as well as leading to short-term changes in phytoplankton community composition (Arrigo, 2005). In their synthesis of eight artificial OIF experiments, De Baar et al. report a linear relationship between diatom size and Fe requirement for growth (2005: 12). Not only did they record a shift from nanoplankton (<10 µm) to mostly microplankton (>10 µm), but the 100-fold increase of Fe concentrations due to OIF provided conditions favorable for growth of moderate (10-30 µm), medium (30-60 µm) and large (>60 µm) diatoms. Moreover, De Baar et al. explain that larger phytoplankton species stimulated by the iron addition would enjoy a relief from grazing pressure in the early stage of the bloom since their specialized zooplankton grazers are not sufficiently abundant to limit their growth rate (2005: 17). This so-called 'growth rate advantage' means that Fe-replete conditions favor the growth of large cells and accelerate the rate at which they may dominate the community response. In fact, diatoms increased in nearly all field experiments, yet, depending on the location the most abundant diatom species varied (Williamson et al., 2012: 477). It has been speculated that this is due to competition and regional differences in species composition prior to the application of OIF (Kudo et al., 2009).

Concerns have been raised about the potential side effect of stimulating the formation of 'harmful algal blooms' (HAB) (Vaughan and Lenton, 2011: 758). These are dubbed harmful since this species of phytoplankton produces a toxin called domoic acid which may negatively affect other marine living resources. Trick et al. explain that OIF could enhance the abundance of such toxic phytoplankton as well as their rate of toxin production (2010). This response was demonstrated in the Southern Ocean and equatorial Pacific (Silver et al., 2010). It has been argued elsewhere that HAB result mainly from coastal eutrophication, whereas the causative link between open ocean OIF and HAB is difficult to predict with confidence (Cloern, 2001).

Moreover, OIF may increase trophic levels (grazing) during bloom and induce changes in grazer communities. Saito et al. (2006) reported an increase in the stocks of microzooplankton (<200 μm) which are primary consumers of phytoplankton in the open ocean (Calbet and Landry, 2004). Their relatively short lifetimes allow for monitoring during days-to-weeks (De Baar et al., 2005: 16), as compared with mesozooplankton (>200 μm) whose lifetimes are longer and more complex. Mesozooplankton predate large phytoplankton and smaller zooplankton while acting as trophic intermediaries to fish and other higher-level consumers. They produce fecal pellets that accelerate sinking of particulate organic matter and thus play an important role in POC export (2005: 16). The grazer response is a key mechanism for regulating the OIF-induced phytoplankton bloom and results in the recycling of carbon through the food web, potentially leading to a decrease in sequestration (Russell et al., 2012). But despite its importance this mechanism is little understood. A major limitation is that the duration of field experiments has generally been too short to allow for meaningful study of the response of mesozooplankton (De Baar et al., 2005: 16).

It has been suggested that OIF may lead to the potential enhancement of fisheries[13]. However, the precise implications for fish stocks are speculative (Williamson et al., 2012: 482). Cullen and Boyd caution that the compounded effects of climate variability and global warming make it difficult to attribute major changes in fisheries to a single cause such as OIF (2008: 299). De Baar contend that our present understanding of OIF impacts on marine pelagic ecosystems is limited to single-celled organisms and ecosystem responses higher up the food chain require further research (2005: 16).

There remains a significant degree of uncertainty regarding the precise changes to marine pelagic ecosystems resulting from individual and sustained application of OIF. Lampitt et al. argue that “The types of change will depend heavily on the proposed method of fertilization but a clear conclusion about either of these is not

[13] This is also cited as one of the main motivations behind the Haida Salmon Restoration Corporation conducting the 2012 unilateral OIF experiment under the leadership of Russ George (Tollefson, 2012).

possible until the large-scale fieldwork and associated modelling has been completed" (2008: 3935).

2.3.3. Changes to marine benthic ecosystems

The impacts of OIF on benthic ecosystems have been scarcely studied and most of our knowledge is inferred from observations of natural fertilization. These suggest that the abundance, biomass and diversity of deep ocean benthic organisms are closely connected to the export of organic matter from the euphotic zone. Benthic biomass levels can be three times higher and abundance up to six times higher in natural fertilization regions of the Southern Ocean than in regions with lower Fe concentrations and lower primary production (Wolff et al., 2011). Lampitt et al. explain that the relation of POC export and benthic ecosystem response is complex and depends not only on the changes in export but also on the composition of particulate organic matter (2008: 3938). Moreover, they argue the benthos is therefore in a complex dynamic equilibrium and may revert to its previous state after elevated POC export declines, suggesting that these impacts are reversible.

Of the 0.4 Gt C yr^{-1} deposited on the deep-seabed, an estimated 96% is dissolved or remineralized every year contributing to air-sea exchange of CO_2 while only 4% is buried in the geological sediment and out of contact with the atmosphere for millions of years (Lampitt et al., 2008, based on data from Tyson 1995, and Jahnke 1996). This natural process of carbon sequestration is driven primarily by benthic organisms. The pH changes resulting from oxygen depletion may adversely affect benthic ecosystems and deep ocean biota by altering the depth at which carbonate minerals begin to dissolve (Oschlies et al., 2010). These biominerals (calcite, aragonite) are required by calcifying organisms such as mollusks, crustacea and deep-sea corals to build their shells, skeletons or reefs (Cao and Caldeira, 2010: 304) and pH changes may therefore limit their habitat (Williamson et al., 2012: 482).

2.3.4. Formation of climate relevant gases

Several studies have examined the potential for formation of climate-relevant gases – i.e. trace gases with positive or negative impacts on the radiation budget – resulting from the short and long-term application of OIF.

The decline in oxygen concentrations caused by OIF-enhanced POC export may generate nitrous oxide (N_2O) or methane (CH_4). N_2O, a greenhouse gas with a global warming potential (GWP) approx. 300-times higher than carbon dioxide[14] may be produced during remineralization of organic matter exported below the euphotic zone (Law, 2008). The potential increase in N_2O emissions from OIF has been thoroughly modeled and has been posited to significantly offset the GHG reduction potential of OIF. In the tropics, the N_2O offset may amount to 40-115% while in the Southern Ocean it is much lower at 10% due to higher oxygen concentrations (Jin and Gruber, 2003). Moreover, the offset is lower for 100-year continuous Fe addition and higher for 10-year application of OIF. Jin & Gruber suggest this is because OIF-induced CO_2 fluxes decrease relatively rapidly while oceanic N_2O emissions remain elevated, thus the degree of the offset increases over time (2003: 2; See Figure 6).

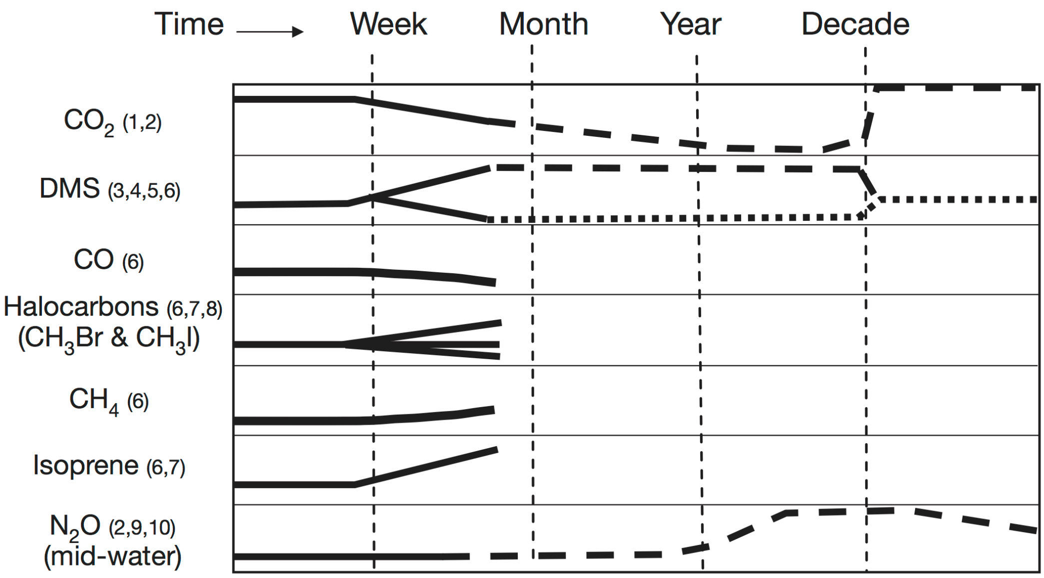

Figure 6: Temporal response of CO_2 and trace gases in surface waters and N_2O in the mid-water column based on the FeAX observations (solid lines) and model output and extrapolations (dashed and dotted lines) of (1) Wong et al. (2006), (2) Jin & Gruber (2003), (3) Turner et al. (2004), (4) Takeda & Tsuda (2005), (5) Levasseur et al. (2006) (observed DMS results extrapolated as dotted line), (6) Wingenter et al. (2004) (observed DMS results extrapolated as dashed line), (7) Moore & Wang (2006), (8) Liss et al. (2005), (9) Law & Ling (2001), and (10) Walter et al. (2005). Source: Law, 2008: 284.

Law (2008) therefore advocates caution and places great importance on long-term N_2O production as a determinant for site location and duration of OIF (2008: 285). Since higher offsets are estimated for short-term OIF (10 years), monitoring would need to continue well over the duration of this period to account not only for carbon

[14] The Global Warming Potential (GWP) of N_2O is estimated at 289 over the next 20 years and 298 over the next 100 years (IPCC AR4 Chp.2, 2007: 212).

flux but also for N_2O production and emissions. Paradoxically, small-scale field studies to date have reported only minor increases in N_2O production (Law and Ling, 2001; Walter et al., 2005), leading some authors to conclude that the offset effects will be dispersed and transient without significant consequences for ecology and climate (Williamson et al., 2012: 481).

By comparison methane (CH_4) emissions resulting from OIF are estimated to be low and "might safely be considered an acceptable consequence" (Cullen and Boyd, 2008: 299). One central reason is that methane[15] is converted to carbon dioxide long before reentering the euphotic zone and resurfacing to the atmosphere (Naqvi et al., 2010).

It has been suggested that OIF may lead to changes in concentrations of other climate-relevant trace gases[16] including tropospheric ozone (Williamson et al., 2012: 481; Law, 2008), hydrogen sulfide (H_2S) (Cao and Caldeira, 2010) and dimethyl sulfide (DMS) but the significance of their alteration is currently unclear (Law, 2008). For the sake of brevity we will only further discuss the latter. Being a cloud-forming gas, DMS enhancement has been debated as a potential geoengineering technique in itself (Latham, 1990; Wingenter et al., 2007). The question then is how large the positive effect on radiative forcing resulting from OIF-mediated DMS production through OIF will be. Williamson et al. estimate that fertilization of 2% of the Southern Ocean could reduce sea-surface temperatures by 2ºC in that region (2012: 481). Studies have furthermore determined that DMS increase is limited to the Southern Ocean while showing no effect or decreasing during OIF in the sub-Arctic Pacific (Levasseur et al., 2006; Nagao et al., 2009), indicating that its climatic relevance as a side effect of OIF is geographically limited.

In closing, it may be relevant to include the offset by CO_2 emissions from the deployment of long-term OIF in this analysis. Based on Harrison's estimates of an iron requirement of 2.4 kg km^{-2} for large-scale OIF, any CO_2 offset derived from mining and refinement of the $FeSO_4$ would be negligible (2013: 14). He further suggests that emissions from deployment may be similarly low but the financial cost and CO_2 offset could prove to be significant if long-term OIF monitoring will be ship-based (2013: 10).

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[15] The Global Warming Potential (GWP) of CH_4 is estimated at 72 over the next 20 years and 25 over the next 100 years (IPCC AR4 Chp.2, 2007: 212).
[16] For an overview of causes and radiative forcing potential of all relevant trace gases, see Lampitt et al., 2008: 3934, adopted as Annex - Table 2.

2.3.5. Impacts on global nutrient balance

Through the addition of a limiting micronutrient (Fe) OIF will lead to the substantial consumption of unused macronutrients at the site of fertilization (Boyd et al., 2004). While this effect is intentional, it may cause several unintended impacts, such as 'nutrient robbing'. According to Gnanadesikan and Marinov this is because OIF, while increasing primary production locally, may use up nutrients from surrounding waters and lead to a decrease in nutrients advected downstream, thereby lowering far-field biological production (2008: 289). Reductions in productivity elsewhere may be significantly large (Gnanadesikan et al., 2003; Aumont and Bopp, 2006) but might only occur as a cumulative result of repeated fertilization events (Cullen and Boyd, 2008: 298). Importantly, the corresponding decline in POC export is unlikely to offset the benefit of long-term OIF, since on average, global levels of unused macronutrients still decrease, leading to enhanced drawdown of atmospheric CO_2 (Gnanadesikan and Marinov, 2008: 289). It has been argued that the regions where CO_2- and nutrient-enriched waters resurface might experience an increase in productivity (Williamson et al., 2012: 481). Nevertheless, the rate at which nutrient robbing may occur, its potential negative or positive impacts on fish production, and crucially, the geographic spread of this nutrient distribution are highly speculative and require further study.

Marinov et al. find that there exists a 'biogeochemical divide' in the Southern Ocean where upwelled deep water splits into two pathways, one going north and sinking to mid-depths, and one going south and sinking again to deep ocean. Each has different implications for OIF. The Subantarctic intermediate and mode water formation region north of the divide controls the magnitude of the biological pump at low latitudes and thus determines global POC export production. The Antarctic deep-water formation region south of the divide may not have any direct impact outside that region but mainly controls air-sea balance of CO2. The implication here is that OIF modifying waters south of the divide may not significantly alter the other while changes to waters north of the divide could lead to widespread effects (Marinov et al., 2006: 964). Sarmiento et al. further contend that nutrient robbing at the Ross Sea site (south of the divide) may have less harmful effects on low latitude biological production compared with another site in the Southern Ocean (2010: 3618). However, the authors caution that local impacts resulting from OIF may persist and that the Antarctic deep-water formation pathway could spread deep-water oxygen depletion into the Pacific Ocean.

2.4. Monitoring and Verification

As has been suggested elsewhere in this thesis, OIF is subject to large spatial and temporal scales that impose severe limitations on our present possibilities to monitor and verify experiments. This is even more so when one considers large-scale applications of OIF, which are currently at the stage of modeling and lack suitable mechanisms for monitoring and verification. Consequently, rather than going into detail about the various monitoring technologies that have been used in previous small-scale field trials[17], we focus this discussion on modeling practices and elaborate the need for further, large-scale field experiments.

2.4.1. Monitoring needs and difficulties

The argument has been made by several authors previously involved in OIF field experiments that the limitations of our current monitoring and verification capabilities make it extremely difficult if not impossible to obtain accurate information on both the effectiveness and environmental impacts of OIF (Williamson et al., 2012: 483). For example, it is difficult to measure oxygen depletion, due to a severe shortage of data on preexisting oxygen levels and distribution (Williamson et al., 2012: 481). Even satellite remote sensing, a main method to monitor phytoplankton bloom development on a daily basis, has its limitations. First, while the increase in biomass observed through a rise in Chl α may be a proxy for increased POC export, it cannot be directly quantified into an amount of carbon exported (ACE CRC, 2008: 8). Second, when OIF is deployed on a large-scale, it may become difficult to distinguish between phytoplankton blooms resulting from the iron addition and those occurring naturally (Williamson et al., 2012: 483). Some commentators argue that given the complexity of OIF, modeling may be our best shot at providing some level of certainty (Watson et al., 2008: 308); it presents an option to predict consequences of OIF without creating adverse environmental impacts in the real world (Cicerone, 2006).

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[17] See Annex – Table 3 for an overview of various measuring technologies including their sampling resolution, adopted from Watson et al., 2008.

2.4.2. Modeling and its limitations

Lampitt et al. indicate that regional modeling of localized field experiments exists but capabilities are much more constrained for global modeling studies to assess both long-term and remote consequences of OIF (2008: 3938). They further suggest that a new generation of ecosystem models is currently being developed that achieve a better integration of the iron cycle. Iron cycling has been lacking from previous models due to its complexities such as the bioavailability and speciation of iron, as well as photochemical processes involving iron (Weber et al., 2005). Nevertheless, modeling has been criticized for being fallible and overly simplistic, relying heavily on the correctness of underlying assumptions and data, while unable to capture all the complexities of OIF, including the vast range of spatial and temporal scales involved (Vaughan and Lenton, 2011). Given the inherent limitations of modeling it is clear why many in the scientific community dealing with OIF advocate the need for vigorous validation of models through experimental and observational data (Lampitt et al., 2008; Williamson et al., 2012).

Perhaps the most important challenge identified is the verification of POC export and subsequent sequestration. Watson et al. indicate that carbon sequestration can only be measured by modeling because calculations involve integration over large temporal (years) and spatial scales (areas over millions of km^2; 2008: 305). However, there are severe limitations in the ability of global biogeochemical models to predict upper ocean production and export (Gehlen et al., 2006) and the tracking of added micronutrients to the fertilization area is difficult as the patch starts mixing with adjacent waters (Gnanadesikan et al., 2003). As a result, Lampitt et al. write: “Our understanding of the mechanisms contributing to export remains incomplete, compromising the ability to successfully predict the ecosystem response to perturbations in iron supply” (2008: 3929).

2.4.3. Need for large-scale experiments

Some authors have argued that our current understanding and lack of observational data on OIF impacts and effectiveness may be improved through a scaling up of field studies (Cullen and Boyd, 2008; Gnanadesikan and Marinov, 2008; Law, 2008; Watson et al., 2008; Williamson et al., 2012). They call for large-scale OIF experiments to overcome the practical limitations of longer time-scales needed for in-situ patch monitoring; measurement-based estimates of carbon sequestered; and monitoring of downstream impacts. Such upscaling from the previous generation of small-scale experiments (1993-2005) would see an increase in ocean area to 100 to 200 km^2 (Lampitt et al., 2008: 3940; Watson et al., 2008: 306) and in time-scales to months and years. Watson et al. contend that such large OIF projects may involve scales too long and too large for direct ship-based observation (2008: 306). They argue that control scenarios could no longer be derived from observation around the patch and surrounding waters but only via modeling. Williamson et al., 2012 further caution that first generation small-scale OIF experiments did not lead to long-term alterations of ocean ecosystems, as they mostly corresponded to the scale of natural ocean fertilization events that subsided within few weeks or months (Williamson et al., 2012: 482). In contrast, there is substantial uncertainty of the extent (both in time and space) of impacts resulting from large-scale OIF[18].

2.5. Costs and Emission Credits

This section analyses the cost aspects related to large-scale research and the deployment of OIF as a geoengineering strategy. We will also address whether emission offset credits could be issued for CO_2 sequestration achieved through OIF.

2.5.1. Research costs

To date there have been no comprehensive studies into the research costs associated with large-scale OIF experiments. Regardless, a few authors have made speculations about the potential costs of upscaling OIF research. Watson et al. (2008) for instance, suggest that the scaling up of experiments to longer duration and larger area will not lead to a linear cost increase. They argue that significant cost increases for the delivery of the $FeSO_4$ from multiple ships or aircraft, monitoring via satellites, research & development and verification will have to be considered. For large-scale research, as for deployment, it is the loss through offsets (such as N_2O production; Law, 2008) and the uncertainty of net carbon sequestration which render any cost analysis of OIF difficult.

[18] For an overview of major uncertainties pertaining to the effects of OIF, see Annex – Table 4, adopted from Watson et al., 2008.

2.5.2. Deployment costs

The traditional assumption has been that the cost of OIF deployment is dominated by the cost of manufacture and delivery of $FeSO_4$. This assumption is based on upscaling of cost estimates for global deployment of OIF, requiring a large fleet of ships (Klepper and Rickels, 2012) and a large stock of fertilizer (9-35 t Fe yr^{-1} to achieve a significant CO_2 offset; De Baar et al., 2005: 20). However, a recent study by Harrison suggests that the fertilizer is no longer the dominant cost factor (2013: 3). The author pins the current price of $FeSO_4$ at US$ 555 t^{-1} Fe, which amounts to less than US$ 0.01 t^{-1} CO_2e for biomass generated. The likely dominant cost factor, Harrison argues, is the cost of covering large areas of the ocean to inject and sustain small amounts of Fe per unit area.

A number of authors provide estimates for the likely cost of large-scale deployment of OIF. Early estimates which support the idea of OIF as a low-cost geoengineering option start from US$ 5 t^{-1} C yr^{-1} sequestered (Ritschard, 1992) or US$ 2 t^{-1} C sequestered over 1000-2000 years (Markels and Barber, 2001). Through simple upscaling of molar ratios reported from various small-scale field experiments Boyd has updated these figures to a cost range of US$ 30-300 t^{-1} C sequestered (Boyd, 2008).

However, Harrison suggests these estimates are still too optimistic and the likely cost of large-scale OIF, at 9.3% POC export and considering the most probable level of loss terms, is US$ 457 t^{-1} CO_2 (or US$ 125 t^{-1} C) sequestered over 100 years[19]. It should be noted that this cost estimate excludes the cost of the $FeSO_4$ input material, administrative services, as well as monitoring and verification. The latter may lead to a significant increase, considering that global deployment and distribution of the fertilizer could require a fleet of ships from as few as 20 to as many as 500 (Klepper and Rickels, 2012).

2.5.3. Emission credits

There is consensus among the scientific community that emission credits should only be granted to geoengineering activities where the amount of carbon sequestered can be verified (Buesseler et al., 2008; Lampitt et al., 2008: 3922;

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[19] At 9.3% POC export, Harrison's most pessimistic scenario results in infinite costs and negative carbon storage, while his most optimistic scenario of loss terms results in a cost of US$ 83 per ton CO_2 (or US$ 23 per ton C) sequestered over 100 years (2013: 16).

Williamson et al., 2012: 477; and others). To qualify as a mitigation method under the IPCC framework, OIF needs to fulfill the IPCC definition of a sink, requiring the carbon to remain out of contact with the atmosphere in excess of 100 years (IPCC, 2007). The prospect of carbon credits has attracted a number of commercial ventures such as Climos, Planktos Science and Ocean Nourishment Corporation despite the reality that no credits are likely to be issued before the safety and effectiveness of the technology can be proven. According to Buesseler et al. there is currently no scientific basis to support a decision in favor of issuing carbon credits for OIF and any such decision could only emerge after uncertainties pertaining to carbon sequestration efficacy, ecological and biogeochemical impacts have been reduced through targeted research (2008: 162). This decision depends largely on the carbon market and the credit issuance criteria adopted by its regulatory bodies.

2.5.4. Potential for rogue ocean iron fertilization

Aside from the false promise of profit from emission credits, large-scale OIF could still prove an attractive venture for wealthy private and corporate investors. Most crucially, as Russ George's very recent unilateral iron addition experiment has shown, OIF can be considered an out-of-the-box, DIY type of technology. First, the cost of a one-off iron dump is relatively low (US$ 555 t^{-1} Fe; US$ 20,000 per day for ship according to Markels et al., 2011; excluding the costs of long-term monitoring and verification expected of genuine scientific research). Secondly, a one-off iron addition can be deployed immediately as long as the venture is small-scale; large-scale OIF requires significant infrastructure development (see above; Vaughan and Lenton, 2011). Thirdly, it can be halted immediately and primary production subsides within a few weeks, though any POC export generated cannot be reversed (Vaughan and Lenton, 2011).

2.6. Governance Challenges

There is disagreement in the scientific community dealing with geoengineering over the need for further research into such techniques to counteract climatic change. A 2011 study by the US Government Accountability Office consulted experts on the matter and found that those who called for further research perceived it either as urgent given the risk of irreversible climate impacts or as an insurance policy to future climate trends (US GAO, 2011). By contrast, those opposing further research perceived the threat of climate change as being not so great to justify GE interventions and pointed to the risks from potential adverse effects of such techniques. This highly opinionated debate exemplifies but one of the governance challenges proposed in this thesis.

Drawing on the results from the detailed analysis of the effectiveness and potential environmental impacts of OIF in previous sections, we formulate the following set of governance challenges. These challenges are unique to the technology and require careful consideration in order to avoid ineffective regulation.

1) **Need for further research –** There is a significant degree of scientific uncertainty surrounding the effectiveness, environmental impacts and underlying biogeochemical and biological processes of OIF that can only be reduced through further research.

2) **Need for large-scale OIF** – There is consensus that further research will require improved modeling capability and needs to be supplemented by observational data from field experiments. Such field experiments will need to cover greater temporal and spatial scales, enhancing the risk of unintended, and potentially irreversible adverse impacts.

3) **Need to enhance monitoring and verification** – Technology and mechanisms for monitoring of environmental impacts and verification of CO_2 sequestration are presently unable to yield sufficiently accurate results. Since OIF will require an upscaling of field experiments, the development of these technologies is essential.

4) **Ineffectiveness of small-scale OIF** – Small-scale field experiments to date have been subject to great variability and have therefore produced inconsistent results. They have thus proven ineffectual as a method for establishing concrete/consistent evidence of adverse environmental impacts of OIF and inconclusive for determining its effectiveness as a CO_2 mitigation strategy.

5) **Uncertain reversibility** – There is no conclusive evidence either supporting or disputing the possibility that large-scale OIF may produce irreversible impacts. No small-scale OIF experiment to date has produced evidence of long-term adverse impacts, yet this may be due to the short duration of monitoring during such experiments. Speculations as to the potential of large-scale OIF to produce such impacts are thus inconclusive.

6) **Unequal distributional effects** – It is currently not possible to determine when and where OIF may create such adverse impacts. However there is evidence that the environmental impacts of the technology will not be distributed equally in terms of geography. How individual or repeated experiments affect ecosystems downstream depends largely on its specific location and its broader situation within global circulation patterns.

7) **Low cost, uncertain benefits –** There is some evidence that large-scale OIF may lead to higher GHG emissions than it offsets. It has also been established that the cost of large-scale deployment is significant and pending substantive evidence of a CO_2 sequestration potential over 100 years, it is likely that no emission credits will be issued for the technology.

8) **Threat of unilateralism** – Despite its shortcomings as a research method, and the lack of a real prospect of emission credits, small-scale OIF has attracted significant commercial interest. It is readily deployable and affordable for wealthy private individuals, corporations, and other unilateral state and non-state actors.

3. Legal Analysis

Having examined the scientific basis underlying the technology and having successfully highlighted the main governance challenges it poses, we turn to our legal analysis of OIF governance. This section explores the suitability of present international legal instruments to effectively regulate OIF and makes recommendations for future governance of the technology. Where relevant, specific reference to the governance challenges identified in the previous chapter is made.

3.1. Existing international legal instruments applicable to OIF

Much of the literature on the governance of geoengineering examines to what extent existing instruments of international law (IL) can be applied to regulate such techniques. The manifold scholarly articles follow a similar structure, including an overview of GE techniques, highlighting the need for a comprehensive regulatory framework, and offering concise analysis of each treaty and norm of international law that may potentially apply to a particular technology. In the author’s view this represents a flawed analytical approach since it gives the false impression that existing legal mechanisms were indeed designed to regulate GE techniques. In fact, quite the opposite is true. The majority of international legal instruments have been in existence well before the advent of geoengineering proposals and were not drafted with the intent to include GE within their regulatory scope (CBD SBSTTA, 2012: paras. 6 and 187). There is no express reference to GE in most preexisting treaties and as a result, many attempts at legal analysis have reinterpreted provisions under these existing agreements in order to determine their applicability to GE.

In this section, we in part echo this standard approach by examining the main treaties and where applicable, relevant norms of customary IL, that apply to OIF activities. However, we take this legal analysis a step further **by making explicit reference to specific governance challenges** identified in the previous chapter. Such an integrated analysis not only yields an answer to the standard question “Does this instrument cover said geoengineering technique?”, rather it seeks to provide a more detailed insight into which particular aspects of the technique are currently regulated, to what extent, and what gaps in the governance of OIF remain.

The key multilateral environmental agreements (MEAs) that lay down rules applicable to the governance of OIF are analyzed below.

3.1.1. UNCLOS 1982

The United Nations Convention on the Law of the Sea (UNCLOS 1982)[20] sets the legal framework for all activities involving the oceans and seas and for the determination of maritime boundaries. Importantly, the treaty contains various provisions related to the protection of the marine environment. UNCLOS draws a distinction between activities taking place on the high seas and within a key maritime boundary, the Exclusive Economic Zone (EEZ) which extends 200nm into the sea. Within the EEZ, states are granted sovereign rights to explore, exploit, conserve and manage living and non-living natural resources within the water column, the seabed and its subsoil (Article 56(1)(a)). Moreover, coastal states have jurisdiction over marine scientific research and over the protection and preservation of the marine environment within the EEZ (Article 56(1)(b)(ii-iii).

Alongside these rights, all State Parties to UNCLOS underlie a general duty to protect and preserve the marine environment and to take all measures necessary to prevent, reduce and control pollution of the marine environment (Articles 192-4). Article 196(1) specifically refers to the "use of technologies under their jurisdiction and control" but does not further define this term. Moreover, there is a general duty on states to ensure that any activities under their jurisdiction or control are "conducted so as not to cause damage by pollution to other states and their environment" and that such pollution does not spread to areas beyond national jurisdiction (Article 194(2)). Pollution of the marine environment is defined in Article 1(1)(4) as the direct or indirect anthropogenic introduction of substances resulting in or likely to result in deleterious effects, such as "harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities". Due to the potential adverse environmental impacts of OIF identified in the previous analysis it is plausible that such activities fall under the definition of pollution as laid out in the treaty (BMU, 2012: 10).

[20] United Nations Convention on the Law of the Sea, Dec. 10, 1982, 1833 U.N.T.S. 397, in force 1994.

On the high seas, the ocean areas outside the EEZ, states enjoy relative freedom to pursue any activity, including scientific research (Articles 87(1)(f) and 257). Ship-based activities such as OIF conducted on the high seas are subject to flag state jurisdiction, i.e. the jurisdiction of the state under whose flag the ship is sailing (Articles 92(1); 94(2)(b); and 217).

Part XIII of UNCLOS contains detailed provisions on the regulation of marine scientific research. The right to conduct such research is granted to all states and competent international organizations but is subject to the rights and duties of other states (generally Article 238; within the EEZ – Article 246(1)). Such research must be conducted for peaceful purposes, with appropriate scientific methods and means compatible with UNCLOS and importantly, “in compliance with all relevant regulations adopted in conformity with this Convention including those for the protection and preservation of the marine environment” (Article 240). Article 246 moreover states in unambiguous terms that marine scientific research by other states within the EEZ of a coastal state requires the consent of that state. In the event that damage to the marine environment results from such research activities conducted by a state or conducted on their behalf, that state will be liable for such pollution damage (Art. 263(3); Art. 235). Furthermore, UNCLOS requires the publication of knowledge derived from marine scientific research (Article 244).

It is also worth mentioning that the Convention upholds the rights and obligations of State Parties under other international agreements compatible with UNCLOS (Art. 311(2) and Art.237), requiring that marine scientific research comply with these agreements. Therefore specific provisions under other agreements ratified by UNCLOS Parties may take primacy over the rules set out in the Convention – this was drafted especially with the development of future rules in mind (BMU, 2012) – but only to the extent that they are compatible with the general provisions of the Convention. This principle is further enshrined in the dumping prohibition under Article 210 of the Convention. UNCLOS thereby subjects dumping to national permitting regimes and global and regional regulation, in order to prevent and minimize potential pollution. Article 210(6) and (4) respectably require that national rules should be no less effective than global rules and standards, while global and regional rules developed by competent international authorities must be progressively re-examined as necessary. In effect, these provisions refer to and must be taken together with the rules on dumping set out under the London Convention and Protocol, further discussed below.

Concluding from the legal provisions under UNCLOS set out above, whether an OIF project may fall under its scope depends primarily on whether it takes place inside an EEZ or on the high seas. If it occurs within the EEZ, and has been given consent or has been mandated by the relevant coastal state, then the experiment underlies the exclusive jurisdiction of that state. If it occurs on the high seas (outside the 200nm boundary), the ship-based experiment underlies the jurisdiction of the state under whose flag the ship is sailing. In both cases, the general duty on states to protect and preserve the marine environment applies, including an express requirement to prevent damage from pollution which applies to OIF only to the extent that it can be proven to result or to likely result in such damage. The precise meaning of "likely to result" is not explained in the Convention text nor does the latter contain any reference to the precautionary approach (further discussed below). Moreover, where an OIF activity is deemed to fall within the definition of pollution under the Convention, states are required to draw up contingency plans to prevent, minimize and eliminate damage to the marine environment resulting from it (Art. 199); prepare and share environmental impact assessments (Arts. 205 and 206); monitoring effects and risks (Art. 204); and cooperate in the development of scientific criteria for the regulation of the activity (Art.201). Lastly, the requirement that states make available information obtained from their environmental impact assessment as well as any marine scientific research conducted is a significant step in the direction of good governance and transparent risk management of OIF technologies.

3.1.2. UNFCCC 1992

With 195 ratifications, the United Nations Framework Convention on Climate Change (UNFCCC 1992)[21] is the most comprehensive international treaty addressing the mitigation of causes and effects of climatic change. At an IPCC Expert Meeting on Geoengineering held in June 2011, participants pointed out that there is significant overlap between the purpose of carbon dioxide removal (CDR) techniques and the IPCC AR4 definition of mitigation which comprises policies aimed at GHG reduction and sink enhancement (IPCC, 2012: 90). However, the expert meeting deferred a final decision on whether to treat CDR techniques as distinct from mitigation for consideration in the working groups of the Fifth IPCC

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[21] United Nations Framework Convention on Climate Change, May 9, 1992, S. TREATY DOC. No. 102- 38, 1771 U.N.T.S. 107, entered into force 21 March 1994.

Assessment Report (AR5) due 2014 (See footnote 2 of the meeting report). The question whether CDR, and by extension OIF, will be considered a mitigation measure may have significant ramifications for the applicability of the provisions of the UNFCCC.

If considered a mitigation method, some core provisions of the 1992 Convention could apply to OIF, including the precautionary principle. The original iteration of the precautionary principle (or precautionary approach) stems from Principle 15 of the Rio Declaration 1992[22]. It posits that where there is a lack of full scientific certainty about the possibility of serious or irreversible environmental harm, this uncertainty shall not be taken as a reason to postpone cost-effective measures to prevent such harm. This principle has been made operational in Article 3(3) UNFCCC which states that "Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects". The treaty subsequently restates Principle 15 to clarify what is meant by "precautionary measures". The author has argued elsewhere that the wording "measures to anticipate" extends the application of the precautionary principle to mitigation measures (Toussaint, 2012: 239). If deemed a mitigation measure, OIF would thus be explicitly governed by the precautionary approach.

On top of the uncertain effectiveness of OIF as a CO_2 mitigation strategy elaborated in our scientific analysis it is difficult to see how the GE method could effectively be characterized as a mitigation measure within the meaning of the IPCC definition. Winter moreover suggests that while climate mitigation is preventive in nature, geoengineering fixes are remedial end-of-pipe technologies (2011: 281). For this reason and unless determined otherwise in the upcoming IPCC AR5, the UNFCCC will not be applicable to OIF activities.

Scott (2013) has argued for the development of an instrument under the UNFCCC to govern policy-related aspects of GE. Furthermore, she suggests that detailed regulation and management should be left to institutions and regimes with a specialist expertise in the particular GE technology. If a decision is taken to incorporate geoengineering, and OIF specifically, into the framework of the UNFCCC, this will raise further questions of whether the technology may be

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[22] Rio Declaration on Environment and Development 31 ILM 876 (1992).

governed by the Kyoto Protocol[23] and whether OIF projects may be eligible under its flexibility mechanisms.

3.1.3. CBD 1992

The Convention on Biological Diversity (CBD 1992)[24] is a multilateral environmental agreement with near universal membership (currently 193 state parties) and deals with the conservation and sustainable use of biodiversity and its components. It contains numerous provisions and substantive guidance relevant to OIF yet no specific binding rules governing the technology (BMU, 2012). Two comprehensive studies prepared by the Convention's Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) have been relied on in support of this thesis and have recently been merged into a scientific synthesis report[25]. Perhaps the most important contribution of the CBD to the regulation of OIF stems from the decisions adopted by its Conference of the Parties (COP) on the issue of climate change and biodiversity.

At its ninth meeting in 2008, the CBD COP explicitly addressed OIF and adopted a non-binding decision establishing a moratorium on all ocean fertilization activities, with the exception of "small-scale scientific research studies within coastal waters"[26]. The decision makes express reference to the precautionary approach, maintaining that OF activities are only permitted if an adequate scientific basis has been established; appropriate consideration of potential environmental risks, social, economic and cultural impacts has been given; and a global, transparent and effective regulatory mechanism is in place. What is striking is the restriction of OIF experiments to small-scale research in coastal waters. It has emerged from our scientific analysis that small-scale field trials to date have proven ineffectual in surmising evidence on the potential adverse impacts of OIF and its effectiveness as a carbon sequestration strategy. Consequently, this loophole in the decision is redundant and the outcome of the decision *de facto* amounts to a total moratorium on OIF activities. Furthermore, the decision represents a reversal of the

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[23] Kyoto Protocol to the United Nations Framework Convention on Climate Change, 10 December 1997, 37 I.L.M. 22, entered into force 1998.
[24] Convention on Biological Diversity, 31 ILM (1992) 818, entered into force 29 December 1993.
[25] For more information, refer to Secretariat of the Convention on Biological Diversity (2009). Scientific Synthesis of the Impacts of Ocean Fertilization on Marine Biodiversity. Montreal, Technical Series No. 45. Available at: http://www.cbd.int/doc/publications/cbd-ts-45-en.pdf [accessed 27/05/2013]
[26] CBD COP 9 Decision IX/16C on Biodiversity and Climate Change UNEP/CBD/COP/DEC/IX/16 (2008), paragraph 4.

precautionary principle as seen in the UNFCCC context; here the threat is not that of climate change and its impacts but that of unregulated OIF.

In a subsequent non-binding COP decision in 2010[27] the CBD moratorium on ocean fertilization was expanded to all climate-related geoengineering activities[28] that may affect biodiversity. Echoing in part the language of the 2008 decision, this time the CBD COP makes reference to Article 14(1)(a) and (b) of the Convention, requiring Contracting Parties to ensure that an environmental impact assessment of a GE activity proposed by the state or a private actor operating under its jurisdiction is carried out. The exception for small-scale scientific research studies remains in place – minus the obsolete reference to coastal waters – yet with the added requirement that these are conducted in a controlled setting, are "justified by the need to gather specific scientific data and are subject to a thorough prior assessment of the potential impacts on the environment"[29]. Clearly, the CBD COP has tightened its clamp on potential rogue geoengineering experiments and thereby effectively on legitimate large-scale OIF research studies.

While the COP decisions establishing moratoria on OIF and other GE activities are non-binding in their own right, the 2010 COP decision includes a reference to Article 3 of the Biodiversity Convention, restating a key norm of international law: States have the sovereign right to exploit their own natural resources in accordance with their own environmental policies, subject to the condition that they do not cause damage to the environment of other states or beyond areas of national jurisdiction. The notion of a state duty to prevent transboundary harm originates from Principle 21 of the 1972 Stockholm Declaration and Principle 2 of the 1992 Rio Declaration, and forms part of customary IL. As part of its duty to prevent transboundary harm potentially resulting from an activity under its control or jurisdiction, a state is required to inform other states prior to carrying out the activity, carry out consultation, monitoring, diligent control and an environmental impact assessment[30]. The latter

[27] CBD COP 10 Decision X/33 on Biodiversity and Climate Change, UNEP/CBD/COP/DEC/X/33 (2010) paragraph 8(w).
[28] The moratorium excludes carbon capture and storage (CCS).
[29] CBD COP 10 Decision X/33 on Biodiversity and Climate Change, UNEP/CBD/COP/DEC/X/33 (2010) paragraph 8(w).
[30] The duties have been codified in Articles 7, 8 and 9 of the *Draft articles on prevention of transboundary harm from hazardous activities* prepared by the International Law Commission, UN Doc. A/56/10. Available at http://untreaty.un.org/ilc/texts/instruments/english/commentaries/9_7_2001.pdf [accessed 27/05/2013]. The ILC Draft Articles are based on existing precedents from case law and treaties. They are said to "offer an authoritative exposition of the existing law", and have been widely cited in international environmental litigation (Birnie et al., 2009).

requirement has been enshrined as a principle of general international law by the International Court of Justice (ICJ) in the *Pulp Mills* case[31].

However, Parson and Ernst (2013) criticize that the duty to avoid transboundary harm is too broad and vague to effectively constrain GE activities. They write,

> "any nation would be within its rights to conduct [geoengineering] field research, even large-scale field trials leading to deployment, so long as it avoids territorial intrusion on non-consenting states or demonstrable hostile intent. As a political matter, many other states would likely exert pressure to stop such activity, and could invoke various broad legal principles to support this pressure, but no current international legal obligation would prohibit it" (Parson and Ernst, 2013: 15).

A second point of critique is that the norm against causing transboundary environmental harm is rarely enforced by an injured state. Abelkop and Carlson argue this is due to the difficulty of establishing causality for harm caused by remote geoengineering activities, and moreover due to the lack of a forum for an injured state to voice its concerns (2012: 131, forthcoming). It quickly becomes clear that while relevant to large-scale OIF activities as a regulatory tool the norm lacks significantly in legal force to prevent potentially harmful large-scale applications of OIF from taking place.

At the latest CBD COP XI meeting in Hyderabad in October 2012 the 2008 and 2010 moratoria were upheld[32]. In a somewhat schizophrenic appraisal of the precautionary approach, the four relevant paragraphs of the decision that apply to GE and OIF affirm the importance of the approach and of customary international law in general, yet note that it may form an incomplete basis for global regulation (paragraphs 8-11). Paradoxically, the COP decision invites Contracting Parties to address the remaining significant gaps in our understanding of the intended and unintended effects of GE on biodiversity. This is difficult to reconcile with its decision to pass a moratorium that essentially prohibits large-scale research on OIF which we have identified through our scientific analysis as instrumental to gain more accurate information on the effectiveness and potential environmental impacts of the technology.

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[31] *Case Concerning Pulp Mills on the River Uruguay* (Argentina v. Uruguay), ICJ Judgment of 20 April 2010, para.204. Available at http://www.icj-cij.org/docket/files/135/15877.pdf [accessed 27/05/2013]

[32] CBD COP 11 Decision XI/20 on climate-related geoengineering (2012); as set out in Annex I to the Report of the Eleventh Meeting of the Conference of the Parties to the Convention on Biological Diversity UNEP/CBD/COP/11/35 (5 December 2012).

Lastly, it must be noted that Article 22(2) of the Biodiversity Convention requires Contracting Parties to implement CBD provisions related to the marine environment consistent with state rights and obligations under UNCLOS.

3.1.4. London Convention and London Protocol

With 87 and 42 Parties, respectively, the 1972 London 'Dumping' Convention and its 1996 Protocol (LC/LP)[33] regulate activities that involve the dumping of wastes and other matter at sea. 'Dumping is defined as "the deliberate disposal at sea of waste or other matter" (Article III.1(a)(i)), with the meaning of disposal being deposition for the purpose of abandonment (BMU, 2012). Since the material is abandoned, adopting a strict interpretation of the activity would qualify the injection of FeSO4 as dumping. The LC regulates activities classified as 'dumping' through a special permitting regime in Annexes II and III.

Under the London Protocol (LP) activities classified as 'dumping' are prohibited and subject to a reverse listing approach. Importantly, the London Protocol will supersede the London Convention[34] and consequently dumping activities will no longer be permitted for those states that are Party to the Protocol. Moreover, the LP requires Contracting Parties to apply the precautionary approach to justify adopting preventative measures even where there is no causative link between inputs and their effects on the marine environment (Article 3.1).

There exists an exemption under both the LC/LP and the 2006 LP for "placement of matter for a purpose other than mere disposal", as long as it does not run contrary to the objectives of the LC/LP (Article III.1(b)(ii)). Thus where an activity is not classified as dumping but as 'placement' then it is not subject to any permit requirement. It has been speculated that scientific OIF research would come under this exemption, whereas deployment of OIF would not since it runs counter to the LC/LP objective of protecting the marine environment (BMU, 2012). By this logic, only small-scale OIF would come under the exemption within the LC/LP framework, despite its inherent inability to produce sufficient evidence for effectiveness of the technology or impacts.

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[33] Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matters, 1972, 1046 UNTS 120, in force 1975; Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter of 07.11.1996, 36 ILM 1 (1997), in force 2006.

[34] The London Protocol entered into force in 2006 and will eventually replace the Convention for those states that are Party to the Protocol. Until then, the two instruments continue to apply in parallel.

In 2008, the Contracting Parties adopted a resolution on the regulation of ocean fertilization, which classified such activities as 'dumping' and thereby brought them within the scope of the LC/LP regime[35]. The Parties' decision exempts ocean fertilization activities that amount to legitimate scientific research (paragraph 8). In 2010, the Parties adopted an Assessment Framework[36] to provide guidance to national authorities when deciding on a case-by-case basis what activities amount to legitimate scientific research. This guidance document sets out criteria for a preliminary assessment, and procedures for an environmental assessment which includes risk assessment, risk management, monitoring, and guidelines on decision-making. While non-binding in nature and part of a legal instrument with much lower membership than the near-universal Biodiversity Convention, the adoption of the Assessment Framework has been taken note of in COP Decision X/29 under the latter (paragraph 58).

In order to get an insight into the deliberation process that ultimately led the Parties of the LC/LP to adopt this Assessment Framework, it is worth examining the report of the Legal and Intersessional Correspondence Group on Ocean Fertilization (LICG) published by the IMO on its website[37]. The July 2008 report summarizes the deliberations of the Parties on key questions such as whether OIF should be classified as dumping under the LC/LP, and if so under which Annex it would fall. The report indicates that there was no consensus on these questions. The majority considered that where the substance was industrial waste injected into the ocean in large quantities the activity would be classified as dumping, whereas if it had been specifically manufactured for the purpose of the activity and in small quantities it would not (paragraph 14). Despite not reaching consensus, the LICG made reference to other international agreements in their deliberations, notably UNCLOS and regional seas instruments and considered the statements of concern issued by UNSESCO-IOC and the CBD. In conclusion, the Parties felt that "though the Convention and its Protocol were the most appropriate legal instruments to regulate this activity, it was not suited to this at this point and amendment would be required to achieve the regulation of the activity necessary" (paragraph 26).

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[35] IMO Resolution LC-LP.1 (2008) on the regulation of ocean fertilization (31 October 2008).
[36] Assessment Framework for Scientific Research Involving Ocean Fertilization, adopted at the 32nd consultative meeting of contracting parties to the Convention on the prevention of marine pollution by dumping of wastes and other matter 1972 (London Convention) and 5th meeting of contracting parties to the 1996 Protocol thereto (London Protocol), LC 32/15 (14 October 2010), Annex 6.
[37] Report of the Legal and Intersessional Correspondence Group on Ocean Fertilization (LICG) - LC 30/4, 25 July 2008, available at http://www.imo.org/blast/mainframemenu.asp?topic_id=1972 [accessed 27/05/2013]

Indeed, the LC/LP process has established itself as the dominant legal mechanism for present and future governance of OIF. It has been repeatedly endorsed by the CBD, UNCLOS (Articles 311(2) and 240), a UN General Assembly Resolution on Oceans and the Law of the Sea adopted in April 2013 (A/RES/67/78) and the outcome document of the 2012 UNCSD (Rio+20 "The Future We Want"). Work on the Protocol's revision is currently underway and it is likely that the Parties to the LC/LP will vote on an amendment to the 1996 London Protocol to finally introduce regulation that specifically addresses OIF. Such an amendment would be legally binding and would create a new type of permit for legitimate scientific OF research (a proposition known as the 'Canadian proposal'; BMU, 2012). It has been argued that such an amendment would involve changes to the category of placement, rendering some types of placement, such as OIF, subject to a permit requirement. A review of OIF governance commissioned by the German Federal Environment Ministry suggests that this provides for a flexible legal instrument that can be adapted to future developments of new types of placement activities (BMU, 2012), with the only major drawback being that a legal amendment takes considerable time. They argue that the Canadian proposal could be strongly enhanced if the LC/LP parties adopt either an interpretative agreement or a further non-binding resolution to accompany the amendment in order to clarify that "ocean fertilization other than legitimate scientific research constitutes dumping" (2012: 89). This option would be in line with a precautionary approach to regulating OIF activities, significantly restricting non-sanctioned, unilateral OIF activities under the jurisdiction or control of the parties without adopting a total blanket ban on further research. The usefulness of this approach essentially depends on the assessment criteria adopted to evaluate OIF proposals and on whether these criteria would *de facto* rule out large-scale OIF.

3.1.5. Enforceability

The MEAs analyzed in detail in the preceding subsections are relevant to the governance of OIF[38] in two ways. First, they all contain binding rules and non-binding guiding decisions previously agreed on by states to regulate activities which may have adverse impacts on the environment. Secondly, even if these agreements

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[38] As noted above, it has not yet been officially determined whether CDR techniques such as OIF qualify as mitigation measures for the purposes of the UNFCCC 1992. We have included the treaty in this discussion in case they may be so classified.

were never intended to regulate OIF activities per se, the relevant rules and guidance must be taken into account when creating new regulation for such activities. This is because some of these rules create legally binding obligations on states – e.g. in nearly all cases a procedural requirement to conduct an environmental impact assessment – and a failure to honor them may leave a state party in breach of that agreement.

Under the Vienna Convention on the Law of Treaties (VCLT) 1969, “a violation of a provision essential to the accomplishment of the object and purpose of the treaty” constitutes a ‘material breach’ of that treaty (Art. 60(3)(b)), which entitles parties to terminate or suspend the operation of that treaty as between them and the state that caused the breach, or as between all parties (Article 60(2)(a)). The VCLT also makes it clear that any provisions in an agreement that apply in the event of a breach take precedence over the VCLT termination and suspension clauses (Article 60(4)). An example of a material breach in this context would be a violation of the general obligation to protect and preserve the marine environment under UNCLOS, Article 192. UNCLOS contains detailed provisions for the enforcement of its obligations by coastal states, flag states and other states that have control or jurisdiction over the activity (Articles 213-222). For example, where OIF is concerned, a flag state must ensure the activity complies with international rules on the protection of the marine environment and adopt national laws and regulations necessary for their implementation (Art. 217(1)), including adequate penalties (Articles 217(8) and 230). Where a state fails to prevent damage to the environment resulting from the activity it will be liable under international law, requiring it to provide compensation or other relief in respect of that damage (Article 235).

If a legally binding amendment to the London Protocol can be successfully negotiated, the obligations it contains would be equally enforceable in accordance with international law (LP 2006, Art. 10(2)). By contrast, the decisions to adopt a moratorium on OF and other geoengineering activities under the CBD 1992 and the resolutions of the LC/LP are non-binding. They are cast in advisory language which may, at best, bestow them a high degree of “political and normative value” (BMU, 2012: 45).

3.1.6. Bottom-up Governance?

So far there exist two main alternatives to traditional command-and-control-style regulation of OIF activities. These are guiding principles developed by academia and codes of conduct adopted by commercial marine geoengineering ventures.

Climos Code of Conduct

Codes of conduct on OIF have so far been published by commercial ventures such as California-based Climos. In an FAQ on their website the company states that they plan on upscaling previous OIF experiments to "moderate scale experimental demonstrations" and define this as 100-200km-a-side with repeated individual additions and with a few years of monitoring, as compared with large-scale applications covering significant percentages of ocean regions over many years to decades and even centuries. They posit: "Conducting OIF experiments on this scale will greatly improve the likelihood that measurements in the patch have the minimum dilution with material outside the patch and will increase the statistical accuracy of carbon sequestration measurements"[39]. While it is true that upscaling is required it should be kept in mind that the CO_2 sequestration potential of OIF can only be effectively estimated using models, due to the large time scales and spatial scales involved.

The code of conduct published by Climos contains multiple provisions that serve as minimum standards. They cover three main topics: protection of the marine environment, diligence in carbon accounting, and transparency (Climos, 2007). The provisions are detailed and quite rigorous, including requirements for environmental impact assessment, independent verification, measurement and deduction of trace GHGs generated, and a statement that no other commercial interests beyond carbon credits are to be pursued by the venture. Moreover, "projects should be conducted at least 500km from shore", effectively placing them outside the EEZ. This means that primary jurisdiction over such projects would lie with the flag-state which should regulate the activity in compliance with its obligations under UNCLOS. Despite its rigor, the Code suffers important drawbacks. For one, it is difficult to see how the 100-year time-length for CO_2 sequestration could be verified through simple measurements of export flux. As our scientific analysis indicates, there are

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[39] Climos 2008. 'Frequently Asked Questions About Ocean Fertilization', available at: http://www.climos.com/faq.php#8 [accessed 27/05/2013]

significant limitations in measuring CO_2 sequestration on such scales. Furthermore, export flux measurements are insufficient since the actual amount of carbon sequestered may vary depending on the region where carbon-enriched water resurfaces. A second drawback of the Climos Code is that it is voluntary and therefore not legally enforceable should the company disregard any of its provisions.

Interestingly, Climos present a different spin on the precautionary approach than previously examined. Instead of invoking the approach as an argument to prevent large-scale OIF, they interpret it as a justification of further research. An explanation on the Climos website reads: "One interpretation of the precautionary principle is that it is an affirmative duty to take measures […] to mitigate serious, irreparable environmental harms such as those posed by climate change. Viewed in this light, and considering the case we have made for the potential mitigating impact of OIF, research into OIF can be viewed as the essence of precaution" (Leinen et al., 2009: 21). By contrast, Winter contends that the crux of the precautionary approach is preventing damage from occurring (2011: 281). It is certainly farfetched to construe the principle as presenting an affirmative duty to take measures, which may themselves create significant environmental harm.

Oxford and Asilomar Principles

Another non-binding proposal has been developed by an interdisciplinary group of academics, commonly known as the Oxford Principles. The group stresses that these are based on principles already applied in the governance of hazardous substances and activities, including hazardous wastes, radioactive substances and GMOs (Rayner et al., 2009: paragraph 6). They are suggested as framework guidance for geoengineering research and are set out as follows:

1. Geoengineering to be regulated as a public good
2. Public participation in geoengineering decision-making
3. Disclosure of geoengineering research and open publication of results
4. Independent assessment of impacts
5. Governance before deployment

At the 2010 Asilomar International Conference on Climate Intervention Technologies, a group of scientific and legal experts have developed a set of five principles for responsible conduct of climate engineering research. The 'Asilomar principles' contain the following recommendations:

1. Promoting collective benefit
2. Establishing responsibility and liability
3. Open and cooperative research
4. Iterative evaluation and assessment
5. Public involvement and consent

It should be noted that the Asilomar principles were originally based on the Oxford principle yet do not include a requirement for timely and accessible publication nor for conduction a prior EIA.

It quickly becomes apparent that both academic proposals significantly overlap with elements of the Climos Code of Conduct, and revolve around common core themes. These themes include transparency, involvement of the public, and thorough assessment. Further, both sets of principles promote public over commercial interests. While these bottom-up governance approaches are voluntary and entail no legal consequences if they are breached, they could potentially provide an important tool for the further development of legally binding regulation and represent a useful source for naming and shaming unauthorized OIF experiments.

3.2. Unilateralism

Unilateralism should be singled out as presenting the most significant governance challenge of OIF. This is because research or deployment – short ‘application’ – of OIF by a corporation, wealthy individual or other unilateral actor is sufficiently flexible to exploit the largest loophole in the nascent governance framework on marine geoengineering: jurisdiction.

Perhaps the most prominent example of an unauthorized unilateral application of OIF and of ‘rogue geoengineering’ more broadly is the recent iron dumping experiment conducted by the Haida Salmon Restoration Corporation (HSRC) under the leadership of U.S. businessman Russ George. We shall explore this recent iron experiment in detail in order to illustrate the difficulty of regulating such unsanctioned unilateral OIF experiments.

3.2.1. Case Study: The Haida Salmon Restoration Corporation

The OIF experiment carried out in July 2012 by the HSRC in consultation with the local Haida indigenous community, involved the injection of 120 t $FeSO_4$ into an eddy in the Pacific Ocean. The dump reportedly resulted in a phytoplankton bloom over 10,000km^2 around the site of injection, situated 320km from the coast (See Figures 7 and 8 depicting imagery from NASA MODIS Aqua satellite taken in the month following the injection[40]). The stated aim of the project was to restore local salmon populations on which the indigenous community has traditionally depended. Though plausible, Mr. George's involvement in a stalled 2008 OIF experiment conducted by the now bankrupt Planktos Corporation casts doubt over the precise nature of motives behind the project. When the Haida OIF experiment came to light in October 2012[41] it sparked international furor and drew vocal criticism from environmental groups such as the technology watchdog ETC Group and Green Peace. This critical response arose partly from the fact that this unilateral application of OIF went unreported for nearly three months and more so due to the uncertain scientific basis on which the operators justified this experiment.

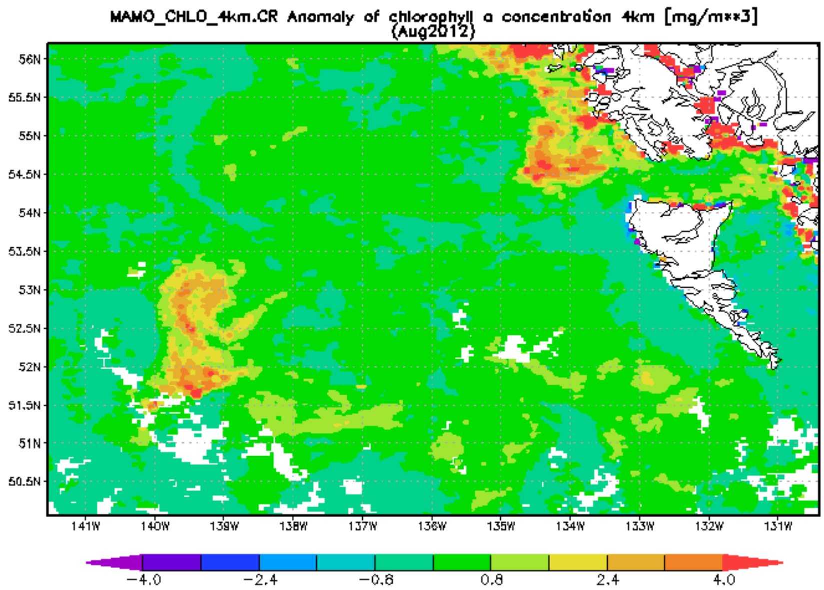

Figure 7: Chlorophyll α concentration anomaly for August 2012. This figure shows that in the location of the bloom, the chlorophyll α concentration is at least 2-4 milligrams per cubic meter (mg / m^3) higher than the 10-year climatological mean, as indicated by the red-orange-yellow

[40] There is some speculation that the observed phytoplankton bloom during this period may have resulted from natural ocean fertilization common to this season (Service, 2012).
[41] See Lukacs, 2012c, http://www.guardian.co.uk/environment/2012/oct/15/pacific-iron-fertilisation-geoengineering [accessed 27/05/2013]

values in the figure. Source: Giovanni/Goddard Earth Sciences Data and Information Services Center/NASA, http://disc.sci.gsfc.nasa.gov/giovanni/giovanni_user_images#iron_bloom_northPac [accessed 27/05/2013]

Figure 8: Pseudo-true color image on August 29, 2012. Source: Robert Simmon, NASA Earth Observatory, Giovanni/Goddard Earth Sciences Data and Information Services Center/NASA, http://disc.sci.gsfc.nasa.gov/giovanni/giovanni_user_images#iron_bloom_northPac [accessed 27/05/2013]

In multiple ways, the Haida experiment amounts to an upscaled one-off application of OIF. The amount of $FeSO_4$ injected was five times larger and the fertilized patch significantly greater than in all small-scale research experiments to date (Tollefson, 2012). Nevertheless, as the amount of substance injected and the ocean area affected are not large enough to yield significant perturbations and corresponding effects on the global climate, commentators have argued the experiment should not be considered large-scale geoengineering. The question remains, why has the experiment drawn such strong negative reactions? Indeed, there are a number of important factors at play.

First, the experiment and post-fertilization monitoring were conducted without governmental or scientific oversight. While George claimed in an interview, "we are sitting on a mountain of golden data like nobody has ever seen" (Hume and Bailey, 2012) and by his own account obtained over 170 million discrete measurements[42], at the time of writing this data has yet to be released. There are serious concerns over the procedures whereby data may have been obtained and whether it may be verified by independent experts[43]. Not only have Mr. George's credentials been called into question – alongside his refusal to name other scientists involved in the project –, Canadian Environment Minister Peter Kent has further branded the iron dump a "non-scientific event" and pledged an investigation and possibly prosecution (Tollefson, 2012).

Secondly, according to the HSRC website the site of injection was situated 320km from the West Coast of British Columbia and the activity was therefore conducted within the EEZ of Canada[44]. Mr. George stated during his previous failed OIF attempt with Planktos that he would operate under a flag of convenience if Canadian national authorities were to deny him permission[45]. However, UNCLOS provisions determine that the location of the experiment within the EEZ gives rise to coastal state jurisdiction. According to Article 56, Canada as a State Party to the Convention has sovereign rights to explore, exploit, conserve and manage marine resources, as well as jurisdiction over marine scientific research and protection of the marine environment. Importantly, it must have regard to the rights of other States and must act in a way that is compatible with the provisions of the Convention. Under Article 73, the coastal state may take various measures including arrest and judicial proceedings to enforce its national laws within the EEZ. One must therefore look to national legal provisions in order to determine whether Mr. George and the HSRC acted lawfully.

Thirdly, the Canadian Government was allegedly aware of the experiment prior to its being conducted and did not adopt measures sufficient to prevent it from taking place (Lukacs, 2012a, 2012b). Both the watchdog ETC Group and Greenpeace

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[42] For more information see the 'data collection page' on the HSRC website, available at: http://science.haidasalmon.net [accessed 27/05/2013]

[43] The answer to this question may no longer lie in the hands of the HSRC, since following a raid of the HSRC office by enforcement officers of Environment Canada on March 27, 2013, by George's account, the entire scientific data collection was removed. For more information, see: http://russgeorge.net/2013/03/30/swat-team-swarms-village-science-office-with-overwhelming-force/ [accessed 27/05/2013]

[44] The EEZ boundary is set at 200nm (approx. 370km).

[45] Sailing under a flag of convenience is a common shipping practice whereby an operator registers a ship in a sovereign state other than that of the ship owner, often with the purpose of evading stricter regulations in the ship owner's country.

claim that the Canadian Federal Government has failed its obligations under the London Convention and Protocol by disregarding the prohibition of OIF other than legitimate scientific research as set out in Resolution LC-LP.1 (2008) and failing to apply the 2010 Assessment Framework (Sousa, 2012; Currie, 2012). Currie (2012) conclude that the OIF activity should therefore not be permitted for the purpose of generating carbon credits or any other commercial ends. Further, in November 2012, the Contracting Parties to the LC/LP specifically addressed the HSRC experiment in a Statement of Concern[46]. The Statement notes, "The Parties re-emphasize that the consultation, notification and reporting provisions of the Assessment Framework are integral to the assessment of any proposed ocean fertilization activity" (paragraph 4)[47]. Nevertheless, one must bear in mind the non-binding legal status of the LC/LP resolutions – and equally of the CBD moratorium – which those decisions support. Again, whether and how these non-binding international decisions can be enforced depends on the extent to which they have been incorporated into national law.

While a determination of the legality of Mr. George's unilateral OIF experiment under Canadian law goes beyond the scope of this thesis, it quickly becomes clear that the international governance framework of OIF as it is presently laid out is ineffective for regulating unilateral application of the technology.

3.3. Gaps in the current regulatory framework

The current international framework for the governance of OIF is woefully incomplete. Having analyzed in detail the existing international instruments applicable to OIF, a number of regulatory gaps become apparent that need to be addressed in the further development of international regulation of the technology. This subsection provides a brief description of these regulatory gaps to inform a subsequent discussion of possible recommendations.

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[46] IMO, Statement of Concern, November 2, 2012, available at http://www.imo.org/blast/blastData.asp?doc_id=14525&filename=J-14%20Rev.doc%20%20 [accessed 27/05/2013]

[47] Güssow (2010) highlight that while the Statement of Concern is not legally binding but may serve as an aid for interpreting provisions and subsequent decisions under the LC/LP.

1) **Lack of specific rules** – There is a shortage of rules that specifically address OIF or marine geoengineering. While the mandate of several key international treaties is broad enough to include OIF activities within their scope, these were not specifically designed to govern geoengineering interventions, and therefore fail to take into account the unique governance challenges of the technology.

2) **Lack of enforceability** – Of the few decisions and resolutions that do specifically address OIF none are legally binding on state parties. At a minimum they should be considered guidance documents, while at best, they may be used to put some political pressure on their signatories and eventually form the basis of binding legislation.

3) **Overlap and inconsistency** – Due to the great number of treaty provisions that potentially apply to OIF, there is significant overlap between agreements. Some treaties such as UNCLOS contain provisions that clarify the primacy of one agreement over the other. Yet provisions such as the precautionary principle are not always cast in the same wording, thus presenting a risk of inconsistent application. Moreover, the relevant international treaties have different levels of participation and membership and as a result not all states will be bound by the same rules. This could potentially result in forum-shopping, enticing operators to choose the location of their experiments or the flag of their ship purposefully to fall under the jurisdiction of a state that is not subject to certain international obligations.

4) **Overly restrictive** – If one overlooks their non-binding nature, the moratoria adopted by the CBD and the LC/LP are overly restrictive mechanisms for regulating OIF. They are too broad so as to block large-scale scientific research that is needed for the technology to go forward. Sugiyama & Sugiyama (2010) relevantly remark that "it is not rational to simultaneously accept a climate emergency scenario and completely prohibit geoengineering". Even where a blanket ban is later followed up by specific permitting requirements (a classic blacklisting approach), such a regulatory response is not suitable to OIF if it only allows for ineffective small-scale (coastal) research.

5) **Flexibility** – OIF like other marine geoengineering technologies is undergoing development and it is likely that legitimate scientific research (especially via non-intrusive methods such as modeling) will yield further answers about its effectiveness and the extent of its impacts. Current regulatory responses must be flexible enough to cater for such changes in scientific knowledge. For example, an amendment to the London Protocol, as envisaged by the Canadian proposal, requires a two-thirds majority vote for adoption and can therefore be a time-consuming process.

6) **Research and deployment –** A trend common to the regulatory responses of the CBD and the LC/LP is to distinguish unauthorized application of OIF from legitimate scientific research. In general this is to be welcomed as a means of rendering unsanctioned OIF unlawful, but fails to take into account the reality that research at a large enough scale amounts to actual deployment of the technology. The author therefore posits that an overly generalized distinction between large-scale research and deployment of OIF is fictional and undermines effective regulation.

7) **Threat of unilateralism** – Russ George's recent experiment has shown that unauthorized, unilateral application of OIF is not currently regulated under international agreements and its legality falls to be determined by national law. While UNCLOS is relevant for determining flag-state or coastal state jurisdiction, and state parties must adhere to general environmental protection obligations, the extent to which these are implemented and subsequently enforced is a matter for national legislation.

4. Recommendations and Conclusion

Drawing on the governance challenges identified through the scientific analysis and on the regulatory gaps identified through the legal analysis, in this section the thesis puts forth a set of recommendations aimed at strengthening the existing regulatory mechanisms applicable to OIF. While by no means exhaustive, these recommendations aim to provide guidance to decision-makers on the types of policies and measures to be taken in the long- and near-term.

4.1. Long-term recommendations

Recommendation 1: *Establishment of a comprehensive, institutionalized global governance framework*

In the long-term, existing regulatory mechanisms applicable to OIF could be greatly strengthened by the establishment of an overarching governance framework. Such an umbrella framework could address the whole spectrum of marine-based CDR methods or all presently known types of CDR measures, depending on the desired scope[48]. A similar attempt is currently being pursued with a focus on regulating SRM technologies, under the Solar Radiation Management Governance Initiative (SRMGI)[49]. The purpose of this governance framework would be to promote international cooperation on this issue and provide a mandate for states to develop more specific rules for a particular GE technology. Rather than creating this framework from scratch, in the author's view, the UNFCCC may be an appropriate starting point. With 195 Parties, the Framework Convention has near-universal participation, is global in scope and has a mandate which by definition should extend to geoengineering activities. With the ultimate objective of stabilizing GHG concentrations at a non-dangerous level, and given the continued shortcomings of conventional mitigation efforts, it is plausible that geoengineering methods may indeed be brought within its scope through a future determination by the COP. Moreover, the UNFCCC enjoys the services of the IPCC, ensuring that decision-making under the Convention and its protocols is kept abreast by changes in

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[48] Due to the distinct nature and governance needs pertaining to SRM methods, for the purpose of effective governance, it is not recommended to lump them together with CDR methods under broad regulation of 'geoengeering'.

[49] Solar Radiation Management Governance Initiative (SRMGI) (2011). *Solar Radiation Management: the Governance of Research.* Environmental Defense Fund, The Royal Society and TWAS, Available at www.srmgi.org/report [accessed 27/05/2013]

scientific knowledge. While the IPCC does not conduct new research or recommend policies, its mandate covers the review of mitigation options[50].

Alternatively, the LC/LP could serve as a governance framework specifically for OIF activities. Indeed, efforts are being increasingly aimed at regulating OIF under the dumping regime and may be formalized through a future amendment to the London Protocol. A major drawback is that only 42 states have ratified the Protocol since its entry into force in March 2006. It is therefore not sufficiently global in scope to prevent an operator from 'forum-shopping', i.e. seeking out laxer jurisdictions to conduct his OIF activity. Keith and Parson (2013) therefore caution, in order to prevent this from happening, "effective governance must thus be backed by government authority and coordinated internationally".

Recommendation 2: *Setting technology-specific rules that are both flexible and legally binding*

Since those existing instruments that are legally binding do not specifically govern OIF and those provisions that explicitly address the technology are not enforceable, efforts at regulating OIF would be greatly enhanced through the adoption of legally binding, technology-specific rules. Such rules would need to be sufficiently flexible to keep step with changes in scientific knowledge on OIF. However, it is difficult to envisage these rules being adopted before an overarching governance framework has been established, and it is unlikely that substantive legally binding rules specific to OIF will emerge outside the margins of such a framework.

4.2. Near-term recommendations

Recommendation 3: *Addressing legitimate scientific research separate from unilateral deployment*

In determining the gaps in the current regulatory mechanisms applicable to OIF, the author has posited that the distinction between large-scale research and the deployment of the technology is fictional, at best blurry. This rests on the finding from our scientific analysis that the potential risks and impacts of either would be the same, since any large-scale field experiment into the effectiveness and environmental impacts of OIF will necessarily produce the effects it seeks to study.

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[50] For more information see http://web.archive.org/web/20080120114538/http://www.ipcc.ch/about/ [accessed 27/05/2013]

Indeed, in its 2012 Report on the Regulatory Framework for Climate-related Geoengineering Relevant to the Convention on Biological Diversity, the CBD SBSTTA notes that where only the scale is considered, there is no clear borderline between field testing as part of research or as part of deployment (2012: 172). Rather than drawing a distinction between two concepts that are factually indistinguishable, regulation will be more effective if it draws a line between *legitimate* large-scale field research and *unauthorized* unilateral deployment[51]. This rests on the assumption that the technology is at present not ready for large-scale deployment and thereby embraces the Royal Society's notion of 'governance before deployment' (2009). Any unauthorized application of OIF should not be considered scientific research.

Recommendation 4: *Further development of bottom-up governance initiatives*

Since top-down regulatory responses take significantly longer to come to fruition, the task of regulating OIF must be complemented by bottom-up approaches. Despite their voluntary nature, current efforts by experts and academia to develop guiding principles are important mechanisms to further the development of international rules and to shape legal expectations in the absence of binding rules. It is crucial that the progressive development of such voluntary instruments reflects the state of the art in terms of scientific research and does not lead to proliferation and inconsistent guidance.

Recommendation 5: *Dis-incentivizing unilateralism*

The threat of increased unilateral application of OIF has been identified as a key governance challenge and remains largely unregulated under existing instruments. The regulatory response has thus far been hasty, leading the international community to adopt overly restrictive – yet non-binding – moratoria on OIF, and subsequently on geoengineering more generally. Abelkop and Carlson correctly attribute this trend to the absence of an appropriate governance mechanism. They write,

> "fear may lead the international community to continue to adopt ad hoc bans that will either prevent needed research on geoengineering or

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[51] Legitimate *small-scale* field research is deliberately omitted since previous analysis has shown it to be an ineffective method done at a scale likely to have negligent environmental consequences. The CBD study further argues that research at a scale that does not affect global climate, by definition, should not be considered geoengineering (CBD SBSTTA, 2012: 172).

> ensure that study and experimentation are conducted secretly and without transparency or oversight. If (as we think likely) such bans do not prevent unilateral action by some states to undertake or authorize geoengineering activities, considerations of the possible adverse transboundary or extraterritorial impacts of particular geoengineering techniques are far less likely to weigh significantly in the decision-making process than if decisions were made under the umbrella of a multilateral governance framework." (Abelkop and Carlson, 2012: 127, forthcoming)

Since one cannot force the advancement of international and even of national regulation prohibiting unauthorized unilateral large-scale OIF, an effective regulatory response needs to remove the incentives for undertaking such activities. In the near-term, this could take the form of a decision or declaration under the UNFCCC/KP framework making it publicly known that no emission reduction credits will be issued for unsanctioned OIF and that such activities will not be eligible under the flexibility mechanisms (applying equally to legitimate large-scale research until there is better knowledge on its potential adverse impacts and until its CO_2 sequestration potential can be proven). This should not be confused with a blanket prohibition of emission credits for OIF. Rather, and if done right, such a declaration would have the effect of dis-incentivizing commercial enterprises while not removing the funding base for legitimate scientific research.

4.3. Conclusion

This thesis has attempted to provide a thorough assessment of the regulation of ocean iron fertilization (OIF). The governance challenges identified through the scientific analysis of OIF processes, effectiveness and impacts render it a classic example of regulation under scientific uncertainty. Moreover, an examination of the suitability of existing international legal instruments applicable to the technology has revealed that there remain significant gaps in the governance of OIF. As a result, OIF activities take place in a regulatory vacuum, neither strictly outlawed, nor explicitly permitted. This vacuum results from the reactionary nature of the law and the slow legal response inherent in the development of binding international rules. It is in this regulatory vacuum that unilateral deployment of OIF thrives, and as the recent Haida experiment has shown, someone inevitably steps up to test the waters. Horton (2011) comments, "the likelihood of uncoordinated interventions is low, but the possibility is real, and the effects could be damaging". Keith and Parson (2013) moreover state they "expect both periodic recurrence of adventurers pushing reckless, scientifically weak projects and rejecting any control, and zealous opponents seeking to prohibit the entire domain of activities". At the time of writing its has been announced that the HSRC will undergo a strategic review and its recent plans for a second iron addition in June 2013 have been suspended[52].

The threat of unilateral application is a particularly thorny issue and requires careful consideration when devising policies on OIF in the near-term. Considering that none of the existing international agreements that apply to OIF activities were designed to cover the technology – let alone geoengineering – the decisions and regulations adopted under the COPs, as well as academic principles and codes of conduct published, implicitly acknowledge the need to regulate unilateral deployment. By the same token, there is an explicit recognition that legitimate, non-commercial scientific research should be allowed to proceed. However, the regulatory responses under two key international agreements have been hasty and overly restrictive, albeit ineffective, as they lack enforceability. The recommendations set out in this thesis propose key policies and measures which address some of the remaining gaps in the governance of OIF and thereby contribute to the progressive development of a thorough and flexible governance framework that is suitable to regulating under scientific uncertainty.

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[52] For more information see Lavoie, 2013, Haida readying for second round of iron dumping in ocean, Times Colonist, April 20, available at http://www.timescolonist.com/news/haida-readying-for-second-round-of-iron-dumping-in-ocean-1.115880 [accessed 27/05/2013] and http://www.timescolonist.com/news/local/dumping-of-iron-into-sea-off-haida-gwaii-suspended-amid-acrimony-1.229839 [accessed 02/06/2013].
It is also worth noting that Russ George has since been relieved of his position of 'chief scientist' and CEO of the HSRC. See http://www.newswire.ca/en/story/1170825/haida-announce-termination-of-russ-george [accessed 27/05/2013]

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Annex

Table 2: Gases and aerosols affecting the radiative balance of the Earth, their current effects, the fluxes to and from the ocean and the ways in which ocean fertilization are likely to alter their influence. Source: Lampitt et al., 2008: 3934

gas	radiative forcing ($W\ m^{-2}$)	ocean to atmosphere supply rate ($mol\ yr^{-1}$)	factors causing increase or decrease	references
CO_2	1.6	-1.4×10^{14}	increased sequestration and carbon export will reduce forcing but not well constrained	IPCC (2001)
methane	0.5	8.0×10^{12}	anoxia increases production	Houweling *et al.* (2000)
halocarbons	0.3	greater than 1×10^{11} (summation of various compounds)	enhanced production due to phytoplankton metabolic processes. Bromo and chloro compounds increase forcing. Iodine compounds may lead to increases in aerosols and albedo enhancing cooling (cf DMS)	Harper (2000), Quack & Wallace (2003) and Smythe-Wright *et al.* (2006)
ozone	0.3		reduction in stratospheric ozone due to increased halocarbons will reduce its negative effect on global warming. Conversely depletion of tropospheric ozone will reduce its radiative forcing	Solomon *et al.* (1994), Dvortsov *et al.* (1999) and Vogt *et al.* (1999)
nitrous oxide	0.1	1.2×10^{11}	increase forcing due to biological production by phytoplankton	Jin & Gruber (2003)
aerosols (direct)	-0.5	3.3×10^{15} ($g\ yr^{-1}$)	any increase in sea salt input will increase aerosol production	IPCC (2001)
DMS (albedo)	-0.7	6.9×10^{11}		

Table 3: Sampling resolution of techniques used to obtain measurements of properties prior to, during, and after an FeAX. Source: Watson et al., 2008: 307

Approach	Technique	Property	Temporal resolution
Remote-sensing	Glider	T, S, O_2, nutrients, particle optics	Hours
	Instrumented buoy	T, S, O_2, bio-optics, particle optics	10s of min
	Satellite	Chlorophyll, eddies (altimetry), temperature	Daily images
	Airborne LIDAR	Chlorophyll, photosynthetic competence	Min
Vessel—underway survey	Undulating tow-body	Chlorophyll, nutrients	Min
	Pumped seawater supply	Biogenic gases (e.g. DMS, CO_2, CH_4 & DMSP), dissolved iron	Min
Vessel—discrete measurements	CTD vertical profiles	T, S, chlorophyll	Hours
	Water bottles/net tow	Water samples for N_2O, phytoplankton (microscopy), grazing (experiments), thorium (export)	$6\ d^{-1}$
Moored instrumentation	Sediment traps	C export and C sequestration	1 measurement $2–3\ d^{-1}$

Table 4: Major uncertainties in the effects of deliberate ocean iron fertilization. Source: Watson et al., 2008: 304

Process	Issue	Finding	Comments
Carbon sequestration efficiency	Carbon fixation in surface water	Variable[a]	Latitude, mixed layer depths + light co-limitation
	Carbon export	None/little/significant[b]	Limited duration of studies
	Depth of carbon export	Poorly constrained	
	Duration of carbon sequestration	Unknown	Unanswerable by observations alone
	Fraction fixed from atmosphere	Poorly known	Likely unanswerable by observations alone
Influence on dissolved oxygen	Formation of subsurface O_2 minima	Poorly known[c]	Potentially harmful, depth dependent
Production of other climate-active gases	Methane & nitrous oxide	No effect/possible enhancement[d,e,f]	Significant warming potential
	Dimethylsulphide	No change/ increase[b]	Some evidence that enhancement is transient
	Biogenic halocarbons	Reduction/no change/ increase[g]	Pertinent to atmospheric oxidation chemistry & particle formation
	Biogenic hydrocarbons, including alkyl nitrates	No change/increase[e,g]	Pertinent to atmospheric oxidation chemistry & particle formation
Effects on ecosystems and biogeochemistry	Phytoplankton species shifts	Mainly towards diatoms[b]	Are shifts transient?
	Mesozooplankton stocks	No change/increase[b]	Localised increases within Fe patch due to arrested vertical migration: duration of study & longer reproductive cycles
	Higher trophic levels	Unknown	Limited duration of studies. Possibility of enhanced secondary and higher-level production[j]
	Macronutrient uptake	Small to significant[b]	Mixed layer depths + light co-limitation
	Reduction of nutrient transport	Important in upwelling regions[h]	Supply flows to other areas cut off, e.g. sub-tropical gyres
	Nutrient remineralization	May affect global distributions	At present only evident from modelling studies[i]

[a]de Baar et al. (2005); [b]Boyd et al. (2007); [c]Natural O_2 minima: e.g. Arabian Sea & east subtropical Pacific, anthropogenic minima: e.g. Gulf of Mexico eutrophication; [d]Law & Ling (2001); [e]Wingenter et al. (2004); [f]Walter et al. (2005); [g]Liss et al. (2005), [h]Cooper et al. (1996); [i]Gnanadesikan et al. (2003); [j]Tsuda et al. 2006