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# A snag for marine nutrient fertilization: decoupled production and export

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1 Interest in nutrient fertilization waned after inconclusive field experiments, but has resurged. Collating Southern Ocean  
2 *in-situ* observations and available fertilization simulations, we find phytoplankton primary production and organic  
3 carbon export are uncorrelated in the largest high-nutrient-low-chlorophyll (HNLC) region, while model estimates cast  
4 doubt on realistic deployments achieving large amounts of carbon removal. Therefore, sequestering carbon by supplying  
5 limiting nutrients appears unproven, and further evidence is required before credits are issued.

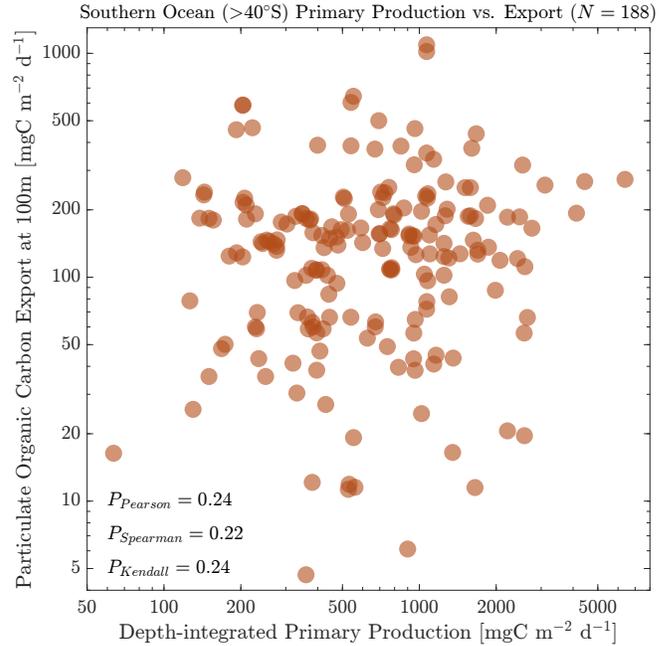
6 Phytoplankton communities can fix >10,000 grams of  
7 carbon per gram of iron incorporated. Although a mi-  
8 cronutrient, iron is also the main limiting nutrient for  
9 phytoplankton in much of the ocean [1]. As a result,  
10 research into marine carbon dioxide removal (mCDR)  
11 originally focused on iron fertilization [2]. HNLC field  
12 experiments demonstrated adding iron stimulated phy-  
13 toplankton biomass as observed in increased chlorophyll,  
14 nutrient and dissolved inorganic carbon drawdown, and  
15 a pCO<sub>2</sub> drop, but the implications for organic matter  
16 export from the upper ocean into the deep, and hence  
17 for atmospheric CO<sub>2</sub> removal, were variable and incon-  
18 clusive [3]. As a result, the end of the 2000s saw calls  
19 for additional research before carbon credits could be is-  
20 sued using this method [4] and arguments to abandon  
21 iron fertilization altogether [5].

22 More recently, however, a scientific consensus has  
23 emerged that gigaton-scale CDR and aggressive emis-  
24 sions cuts are required to meet internationally agreed

25 climate limits [6]. This has led to increased interest  
26 in mCDR, including a resurgence of attention towards  
27 nutrient fertilization [7, 8]. This resurgence includes  
28 renewed interest in research (*e.g.* plans by Exploring  
29 Ocean Iron Solutions (ExOIS) to conduct trials across  
30 the northeast Pacific [7, 8]) but also, the largest issu-  
31 ing of mCDR-based carbon credits to date by the Israeli  
32 company Gigablue (Associated Press Report).

33 Many of the original questions about nutrient fertiliza-  
34 tion that led experts to counsel caution before issuing  
35 carbon credits 17 years ago still persist [4]. It is therefore  
36 useful to assess what new oceanographic observations  
37 and modeling results, including those observations gath-  
38 ered since the original iron fertilization field experiments,  
39 might indicate about fertilization’s efficacy. Here we as-  
40 sess observational results and modeling studies from the  
41 Southern Ocean. Observationally we focus on the re-  
42 lationship between primary production ( $p$ , mgC/m<sup>2</sup>d),  
43 depth-integrated) and particulate organic carbon (POC)

44 exported from the upper ocean ( $f$ , mgC/m<sup>2</sup>d, at 100 m).  
 45 The  $p$  and  $f$  relationship is examined because it remains  
 46 uncertain if an increase in  $p$  translates into a correspond-  
 47 ing increase in  $f$  or durable carbon sequestration [9]. For  
 48 instance, a 2013 compilation of Southern Ocean  $p$  and  $f$   
 49 measurements reported an inverse relationship between  
 50 export efficiency  $f/p$  and  $p$  [10], but this inverse rela-  
 51 tionship may be spurious. [11].



52 To clarify if  $f$  increases with  $p$  we mined the observa-  
 53 tional oceanographic literature for coincident Southern  
 54 Ocean  $p$  and  $f$  *in-situ* measurements. Our approach  
 55 used an automated pipeline developed for a global sedi-  
 56 ment trap POC flux database [12]. Figure 1 shows this  
 57 exercise’s results. By any correlation metric,  $p$  and  $f$   
 58 at 100m are not significantly related ( $P > 0.2$ ). This  
 59 lack of correlation can be considered representative of  
 60 the whole Southern Ocean; the measurements’ longi-  
 61 tudes are approximately uniformly distributed between  
 62 180°W-180°E, and their latitudes are approximately uni-  
 63 formly distributed between 40-70°S (Online Methods).  
 64 15% of measurements are from poleward of 70°S in the  
 65 Ross Sea, but the correlations remain insignificant ( $P >$   
 66 0.2) without these data. Thus, Figure 1 demonstrates  
 67 unambiguously that in the Southern Ocean, higher  $p$   
 68 is not associated with higher  $f$ . Both quantities are  
 69 also highly variable, spanning  $>100\times$  ranges, underscor-  
 70 ing the difficulty of observationally linking the organic  
 71 carbon fixation to its removal from dynamic environ-  
 72 ments.

73

74 **Fig. 1:** Coincident Southern Ocean measurements of  
 75 depth-integrated primary production ( $p$ ) and POC export  
 76 ( $f$ ) at 100 m are uncorrelated.

77 This non-correlation is mechanistically surprising be-  
 78 cause  $p$  and  $f$  are inextricable; the organic carbon ex-  
 79 ported via the biological pump is a portion of that fixed  
 80 via primary production. Several factors may ‘decouple’  
 81 these fluxes. In highly advective, turbulent environments  
 82 like the Southern Ocean, primary production in one lo-  
 83 cation may contribute to export in another place and/or  
 84 a later time even at a depth as shallow as 100m. This  
 85 would not be an issue *per-se* for nutrient fertilization’s ef-  
 86 fectiveness, but would hamper efforts to measure, report,  
 87 and verify any carbon sequestration. Heterotrophs and  
 88 viruses [13] can also be limited by the same nutrients as  
 89 autotrophs [14, 15]. If community respiration or viral ly-  
 90 sis increases commensurately with gross primary produc-  
 91 tion, export would not increase. In addition, if zooplank-  
 92 ton growth rates are differentially temperature-limited  
 93 vs. phytoplankton as evidence suggests [16] and export  
 94 is dominantly due to fecal pellet production – both of  
 95 which have been argued for some HNLCs – increased

96 primary productivity might not lead to increased ex- 130  
97 port. Zooplankton dynamics may also play a role; mod- 131  
98 els suggest zooplankton grazing, not iron availability, 132  
99 limits Southern Ocean summer phytoplankton biomass 133  
100 [17]. Lastly, in ballast-driven export systems like the 134  
101 Southern Ocean the coccolithophores and diatoms driv- 135  
102 ing export through ballast may not be the beneficiaries 136  
103 from increased nutrients, because they could be outcom- 137  
104 peted by equally abundant bloom-forming phytoplank- 138  
105 ton like dinoflagellates [18]. Altogether, multiple plausi- 139  
106 ble ecosystem states could lead to the  $p$  and  $f$  decoupling 140  
107 seen in Figure 1.

108 Note this lack of correlation is, at best, indirect ev- 143  
109 idence that nutrient fertilization may not lead to en- 144  
110 hanced export in HNLCs. Natural co-variations in a 145  
111 system are not equivalent to intentional perturbations, 146  
112 which can both provoke different responses due to *e.g.* 147  
113 the amplitude or timescale of the perturbation, or be 148  
114 designed to maximize the probability of a desired re- 149  
115 sponse. Furthermore, the relationship between nutrient 150  
116 fertilization and export changes may be different for ad- 151  
117 ditions of other nutrients in other regions, such as nitro- 152  
118 gen to oligotrophic gyres, though export in these regions 153  
119 contributes far less to carbon storage by the biological 154  
120 pump than high latitude export. Nonetheless, the *in-situ* 155  
121 measurements discussed above illustrate the biological 156  
122 pump’s complexity and variability, and are consistent 157  
123 with the inconclusiveness of past iron fertilization field 158  
124 experiments [3].

125 We also compiled a dataset of nutrient fertilization mod- 160  
126 eling studies that partially or completely alleviate iron 161  
127 limitation for the entire Southern Ocean (Table 1). All 162  
128 modeling studies apply unrealistic idealized deployment 163  
129 scenarios, e. g. doubling phytoplankton growth rates 164

or removing iron limitation across the Southern Ocean.  
These different approaches complicate study-to-study  
comparison, but there is a clear divide in C uptake  
estimates between 1990s models and those after 2005,  
likely because the 1990s models are simple biogeochem-  
ical models that lack iron and nitrogen cycles and zoo-  
plankton grazing. If these early estimates are excluded,  
model-estimated annual carbon uptake is  $0.6\pm 0.3$  PgC/yr  
(mean $\pm$ std. dev.). Since gross annual emissions are cur-  
rently  $\sim 11$  PgC/yr, this seems a significant contribution.  
However, applying these model deployment scenarios to  
the real ocean would require sustaining dramatic biogeo-  
chemical changes for decades, e.g. adding enough iron  
over the entire Southern Ocean to completely remove  
iron limitation or double phytoplankton growth rates.  
As these scenarios are unrealistic and extreme, model  
estimates should be considered an upper bound, not a  
likely outcome. This implies any realistic nutrient fer-  
tilization deployment could only contribute a fraction  
of the carbon uptake estimated in these model scenar-  
ios, hence a small part of a 2°C-compliant mCDR mix-  
ture.

Nonetheless, petagram-scale CDR in these simulations  
implies a positive correlation between  $p$  and  $f$ , since nu-  
trient addition yields ocean carbon uptake. This ap-  
parent discrepancy with observations (Fig. 1) could  
be due to models overestimating the  $p$ - $f$  relationship’s  
strength due to neglected particle dynamics or plankton  
ecosystem processes [8], or due to models integrating  
over larger spatial scales than observations which may  
miss production in one place resulting in export some-  
where else nearby. This apparent contradiction could  
be resolved by increasing the resolution or ecological so-  
phistication of such models. Given the spread in model  
estimates of carbon removal from nutrient fertilization,

165 it would also be valuable to consistently apply relevant  
166 benchmarks for model validation such as the marine iron  
167 distribution [19] across a spread of models to generate  
168 a high-confidence cross-model estimate of fertilization's  
169 net carbon removal potential. Since few of the compiled  
170 studies investigate durability and additionality, future  
171 modeling research should also build simulations involv-  
172 ing repeated realistic fertilizations over long time scales  
173 as required to avoid a termination shock via the return of  
174 respired deep carbon via ventilation. Future basin-scale  
175 modeling research should also consistently examine the  
176 consequences of side-effects like nutrient robbing, deoxy-  
177 genation, or harmful algal blooms that decrease carbon  
178 removal efficacy or cause negative ecosystem effects as  
179 has been performed for small-scale fertilization patches  
180 previously [20].

181 In summary, modeling studies indicate that nutrient fer-  
182 tilization could at best be a secondary part of a 2°C-  
183 compliant mCDR portfolio, while co-located primary  
184 production and export measurements suggest increased  
185 primary production does not correspond to increased ex-  
186 port in the Southern Ocean – the ocean's largest and  
187 best-studied HNLC system. If increasing primary pro-  
188 ductivity by adding nutrients does not increase export,  
189 the carbon produced is not durably stored, so no addi-  
190 tional atmospheric CO<sub>2</sub> is actually sequestered. Both  
191 further observational and modeling research would be  
192 valuable for establishing nutrient fertilization's potential  
193 [7]. However, until these efforts can demonstrate nutri-  
194 ent fertilization is both safe and effective, there is as  
195 much reason for caution about issuing nutrient fertiliza-  
196 tion carbon credits now as there was previously.

197 **Acknowledgments:** This work was partially supported by the Schmidt Sciences project CALIPSO.

Ocean Carbon uptake (Pg)	Period	Rate (PgC/yr)	Scenario	Fertilization Method	Reference
152	100 years	1.52	3D GCM + BAU A2 post 1990	Full PO <sub>4</sub> removal	Sarmiento and Orr, 1991 <i>Limnology and Oceanography</i>
212	1990 - 2090	2.12	Box model + BAU IA2	PO <sub>4</sub> depletion of 1.5 mmol m <sup>-3</sup> in high latitudes	Joos et al., 1991 <i>Nature</i>
136 - 204	100 years	1.36 - 2.04	Box model	Full surface PO <sub>4</sub> removal	Peng and Broecker, 1991 <i>Nature</i>
106	100 years	1.06	3D GCM, BAU	Full surface PO <sub>4</sub> removal south of 40S	Kurz and Maier-Reimer, 1993 <i>Global Biogeochemical Cycles</i>
159	100 years	1.59	3D GCM, estimate is sum across all HNLCs	Full surface PO <sub>4</sub> removal	Matear and Wong, 1999 <i>Greenhouse Gas Control Technologies</i>
32	2010 - 2100	0.36	Historical + BAU IS92a	Southern ocean macronutrients reduced by half	Zeebe and Archer, 2005 <i>Geophysical Research Letters</i>
70	2000 - 2100	0.7	Pre-industrial + rising atmospheric CO <sub>2</sub>	Mixed layer Fe addition to 2 nM	Aumont and Bopp, 2006 <i>Global Biogeochemical Cycles</i>
26	100 years	0.26	Pre-industrial + fixed atmospheric CO <sub>2</sub>	Removal of Fe limitation	Zahariev et al., 2008 <i>Progress in Oceanography</i>
77	5,300 years	0.58	Equilibrium run*	Removal of Fe limitation	Zahariev et al., 2008 <i>Progress in Oceanography</i>
73	2000 - 2100	0.7	SRES A2 + rising atmospheric CO <sub>2</sub>	Double all phytoplankton growth rates south of 30S	Oschlies et al., 2010 <i>Biogeosciences</i>
98	2020 - 2100	1.2	RCP 8.5 + rising atmospheric CO <sub>2</sub>	No Fe limitation mask applied south of 40S	Keller et al., 2014 <i>Nature Communications</i>
96	3,100 years	0.73	Equilibrium run* with inverse model	Southern Ocean nutrient depletion	Fu and Wang, 2022 <i>JGR Biogeosciences</i>
45	2005 - 2100	0.47	RCP 8.5 + rising atmospheric CO <sub>2</sub>	Mixed layer Fe addition to 2 nM globally	Tagliabue et al., 2023 <i>Global Change Biology</i>

**Table 1:** Summary of survey of modeling literature. Each row corresponds to a study. Columns from left to right show estimated ocean carbon uptake (PgC), the period covered by each study, the estimated carbon uptake rate, the climate scenario or Earth system model used, the fertilization method implemented, and reference information for each study. For complete reference information and details of equilibrium run calculations\* see the Online Methods section.

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# Online Methods for “A snag for nutrient fertilization: decoupled production and export”

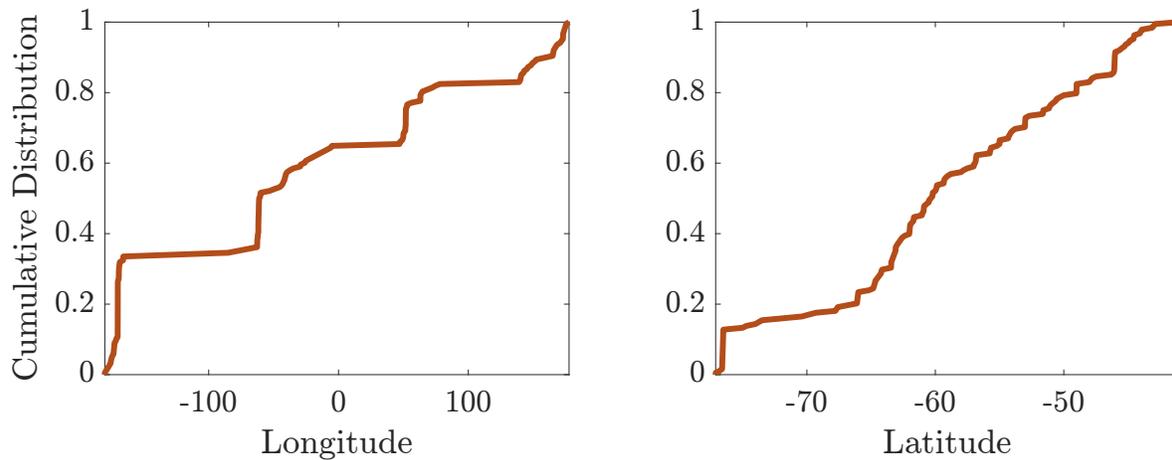
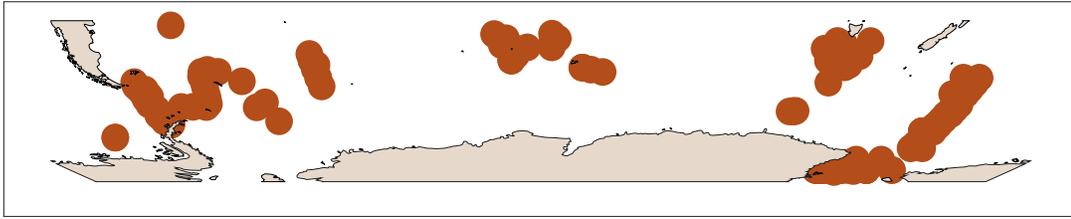
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1 We mined the oceanographic literature for coincident Southern Ocean  $p$  and  $f$  measurements. Our  
2 pipeline was an automated workflow recently developed for a global sediment trap particulate organic  
3 carbon flux database [1]. We searched for paired  $p$ - $f$  measurements, but also for standalone  $p$  data  
4 that could be matched with  $f$  data from Ramondenc et al. [1]. However, for the single  $p$  measurements  
5 not already published with an associated  $f$  measurement, no  $f$  data were available within a  $10^\circ$  radius  
6 and the same year. 140  $p$ - $f$  measurement pairs were from the comprehensive 2013 database compiled  
7 by Maiti et al., [2]; we also found 65 others published since, bringing the total sample size to 205. All  
8 data, citations, and pipeline code will be archived via Zenodo and the DOI will be reported here if the  
9 manuscript is accepted for publication. We then excluded 5 measurement pairs with  $f = 0\text{mg/m}^2/\text{d}$   
10 as the logarithm of 0 is undefined, and 6 measurement pairs with  $p \leq 50\text{mg/m}^2/\text{d}$  as well as 6  
11 measurement pairs with  $0 < f \leq 3.6\text{mg/m}^2/\text{d}$ , following the measurement thresholds where additive  
12 noise dominates measured signals identified in Cael et al. [3]. Note  $f$ ’s 100 m reference depth makes  
13  $p \leq 50\text{mg/m}^2/\text{d}$  equivalent to a depth-averaged threshold of  $0.5\text{ mg/m}^3/\text{d}$  as in Cael et al., [3], and  
14 repeating that paper’s threshold estimation analyses on the dataset compiled here yields an equivalent  
15 result. This leaves a total of 188 Southern Ocean  $p$ - $f$  measurement pairs, for which we calculate the  
16  $P$ -values of the Kendall and Spearman correlations, as well as the  $P$ -value of the Pearson correlation  
17 of  $\log(p)$  and  $\log(f)$  following the approximate log-normality of  $p$  and  $f$  shown in Cael et al., [3]  
18 (Spearman and Kendall correlations are unaffected by log-transformation).

19 Studies included in our compilation of modeling literature are as follows [4, 5, 6, 7, 8, 9, 10, 11, 12,  
20 13, 14]. For studies which used equilibrium runs [10, 13] we calculated a rate using an independent

21 estimate of the mean sequestration timescale of export in the Southern Ocean [15]. If the Southern  
22 Ocean is defined as  $>40^{\circ}\text{S}$ , then the mean sequestration timescale is 132 years in [15].



23  
24 **Fig. S1:** Locations of  $p$  and  $f$  measurements show coverage across the Southern Ocean. Conclusions  
25 from  $p$  and  $f$  correlation exercise are therefore representative of the Southern Ocean as a whole.

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