Uptake Rates as Fundamentals of Iron Availability to Phytoplankton

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What determines the bioavailability of iron to phytoplankton?

Fundamentals of Fe availability

Interactions and ecosystem processes

Shaked and Lis, 2012
Fundamentals of Fe availability

Emphasis on kinetics - Using uptake rate constants ($K_{in}$) for comparisons & extrapolation to the environment

Chemical speciation and kinetics

Uptake pathways & rates

Lis, Shaked, Kranzler, Keren and Morel. 2015. ISME Iron bioavailability to phytoplankton: an empirical approach
Compiling 5 decades of uptake studies:

- Do phytoplankton differ in their ability to acquire Fe?
- Are there lower/upper limits to uptake rates?
- Which Fe complexes are more/less available?
- Can lab studies help define Fe availability in natural environments?
Compiling 5 decades of uptake studies:

18 studies from 13 research groups
Short term and long term (growth) uptake
15 phytoplankton species and 28 strains
5 major divisions (Euks & Cyanos)
16 Fe-substrates

Stringent data selection criteria
(Fe limited cells, log phase, [Fe] below that of $V_{\text{max}}$, etc..)
Uptake rate basics & selection criteria

Steady state

Intracellular Fe

Uptake rate

Fe-replete

Fe limited

Time (hrs)
Uptake rate basics & selection criteria

\[ \rho = k_{in} \cdot [S] \]
Uptake rate basics & selection criteria

**Organic ligand strength & concentration**

[Fe'] in the medium

**Strong Ligands – FeDFB**

**Inorganic Fe – limited by low solubility**

**Inorganic Fe – buffered by EDTA**

\[ \rho = k_{in} \cdot [S] \]
Uptake of inorganic Iron (Fe')

- Large cells
- Small cells
Surface area normalized uptake ($k_{in}/S.A$) is similar among all studied eukaryotes.

\[ \rho = k_{in} \cdot [S] \]

\[ k_{in} = \frac{\rho}{[S]} \]

Regression line:
Direct proportionality between parameters and $R^2 = 0.94$
Uptake of siderophore bound Fe (FeDFB)

Regression line:
Direct proportionality between parameters and $R^2 = 0.9$
Uptake of Fe' and siderophore-bound Fe (FeDFB) are compared.

Surface area normalized uptake ($K_{in}/S.A$) is similar among all Euks for Fe' and for FeDFB. But Fe' $>>$ FeDFB ($\times 1000$).

Graph showing:
- $k_{in}$ vs. uptake rate / [Fe Sub]
- Data points for haptophyte, diatom, dinoflagellate, and green algae.
- Linear regression equations:
  - Fe' (inorganic): $y = 9.25E-11x$, $R^2 = 0.958$
  - FeDFB (Fe-siderophore): $y = 1.07E-13x$, $R^2 = 0.881$
The bioavailability envelope
Empirical results of lab studies with euks

Compare with other organisms, field studies, different Fe substrates...
$k_{in}/S.A$ is similar among all studied organisms for Fe'.

FeDFB uptake of cyanos is slower than in euks.
The bioavailability envelope: comparing Fe substrates

[Graph showing the bioavailability envelope with different Fe substrates compared to siderophore, porphyrin, fresh ferrihydrate, saccharide, organic amine, natural ligands, Fe-dPS, and humic acid.]
The bioavailability envelope: comparing Fe substrates

More bioavailable Fe substrates
Less bioavailable Fe substrates
Conclusions and Implications

- Fe uptake rates of defined substrates can be predicted according to cell size.

- We present a convenient framework for addressing bioavailability by comparing across Fe-substrates and organisms.
Conclusions and Implications

- All phytoplankton are limited by the same fundamental physical, chemical or biochemical factors. Uptake systems have evolved to operate at their maximal efficiency.

- Phytoplankton may employ a similar iron uptake mechanism: **reductive Fe uptake**
  
  Experimental data for ~10 cyanos and ~30 euks!!

- If phytoplankton cannot further increase uptake rates, a competitive advantage in Fe-limited waters must be gained through alternative means.  
  
  Decrease cell size, decrease Fe demands, use alternative Fe sources
Availability of Solid Phase Fe to Phytoplankton: Defining major factors at play

Which physico-chemical form can the cell access?
- Colloidal/ Particulate (directly ingested)
- Dissolved (generated from the particles)

How soluble is the mineral? (chemical reactivity, [ligand], light etc...)

Can cells enhance mineral dissolution rate?
- Removing Fe’ (shifting equilibrium)
- Active dissolution by phytoplankton
- Team-up with bacteria (siderophores)

Mineral residence time in upper water

Can phytoplankton keep mineral Fe at the ocean surface?

Availability extracted from solubility & dissolution rates

Add bio-mediated dissolution

The whole pFe pool is available

Longer - availability
Dust-Fe capturing and modification by natural *Trichodesmium*
Dust-Fe capturing and modifications by natural *Trichodesmium*

Centering of Fe-rich dust

*In situ* association with Fe-rich particles

Synchrotron study with Satish Myneni
Sensing of Fe in particles by *Trichodesmium*

<table>
<thead>
<tr>
<th>t₀</th>
<th>1 hour</th>
<th>1.5 hour</th>
<th>24 hour</th>
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</table>

**Index**

- Natural dust
- Acid cleaned dust
- Fe coated dust

Ave of 9 Exps
30 colonies in each

**Interaction**, **Movement**, **Retention**
Sensing of Fe in particles by *Trichodesmium*

**t₀** | 1 hour | 1.5 hour | 24 hour
---|---|---|---
![Biogenic Silica](image1)
![Fe coated biogenic silica](image2)
![Quartz](image3)
![Fe coated quartz](image4)

Graph showing short term interaction vs. overnight retention for biogenic silica, quartz, and Fe coated biogenic silica and quartz.
Dust-Fe capturing and **modifications** by natural *Trichodesmium*

Low level assay for $^{55}$Fe-ox dissolution with Sid
Dust-Fe capturing and modifications by natural *Trichodesmium*

**Bio-mediated $^{55}$Fe-ox dissolution**

- **Fe within cells**
- **Diss Fe with cells**
- **Diss Sid-Fe (abiotic)**

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Dust-Fe uptake by natural *Trichodesmium* Assisted by Bacteria

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55Fe-Ox, Natural colonies, Red Sea, Mar 2016
Phytoplankton may actively mine Fe from minerals and effect their fate in the ocean.

Thank you.