

沿岸生態系保全と持続可能な 生態系サービスの利活用にむけて ～統合沿岸生態系モデルによるアプローチ～

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サンゴ礁生態系を取り巻く様々な環境変化

グローバルな要因



台風の巨大化？、海水準上昇など

ローカルな要因



栄養塩の流入など

Key questions and objectives

How does the ecosystem response to the multiple environmental changes?

生態系は複合的な環境変化に対しどのように応答するか？

How to mitigate/recover from the recent degraded situations of the ecosystems?

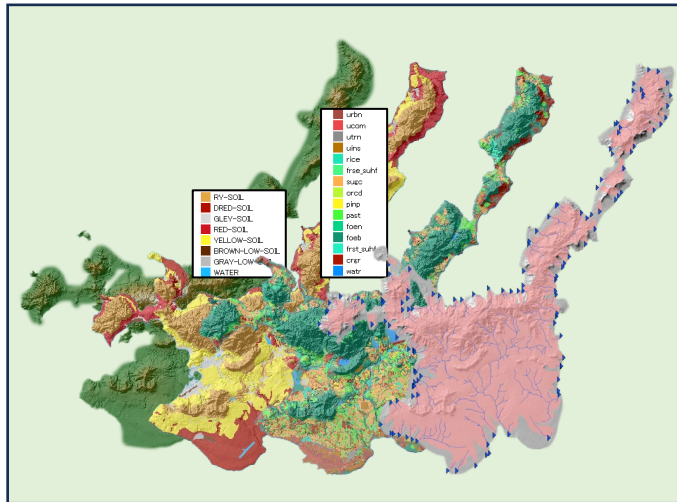
近年の生態系の劣化を緩和ないしは回復させるための方法は？

To develop the “Socio-Ecological System” framework for sustainably using ecosystem services.

生態系サービスを持続的に利用していくための社会-生態系統合フレームワークの構築



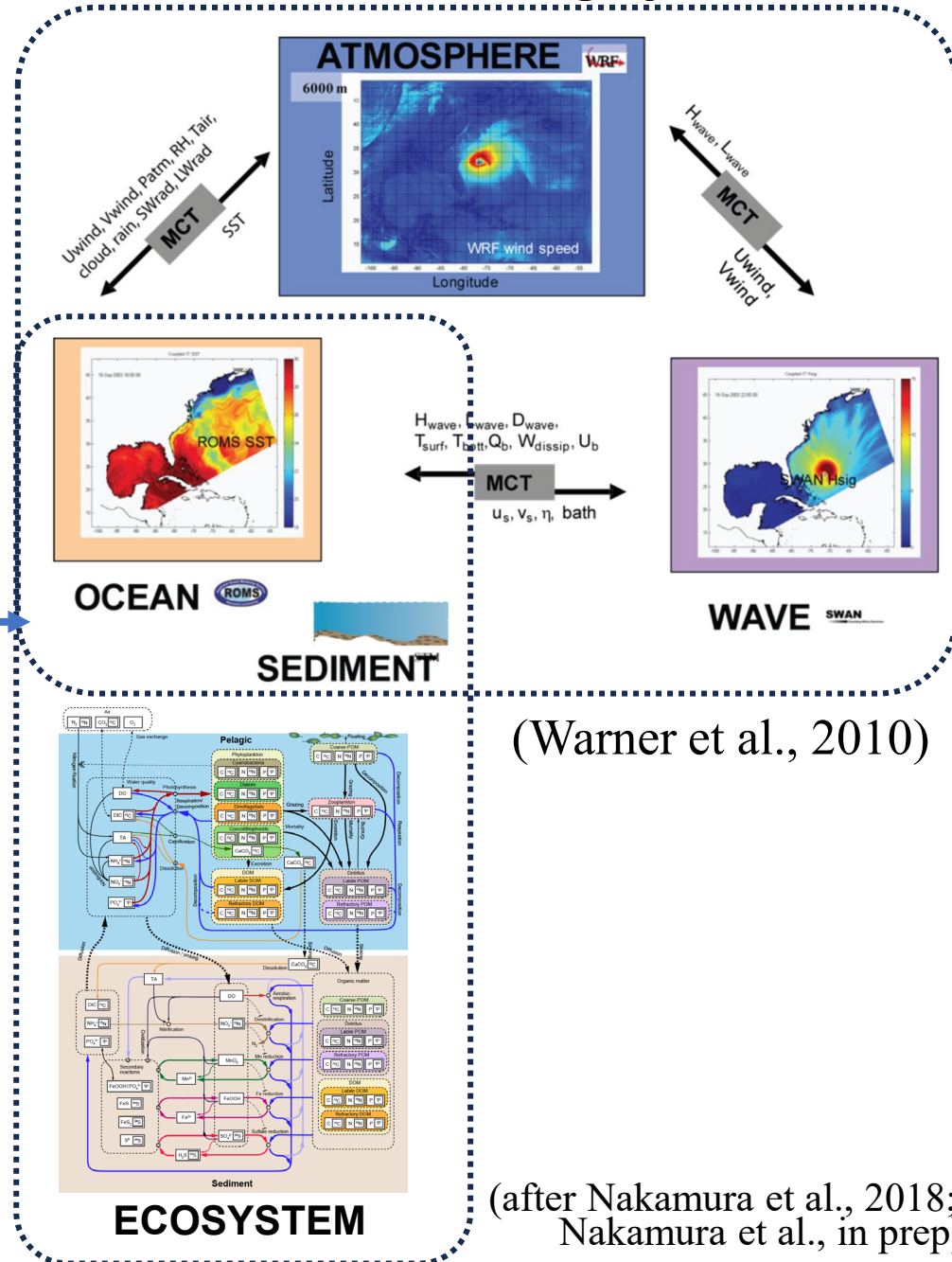
Framework of the Integrated land-ocean-ecosystem modeling system



S+ LAND

(Bieger et al., 2017)

COAWST modeling system



Study site

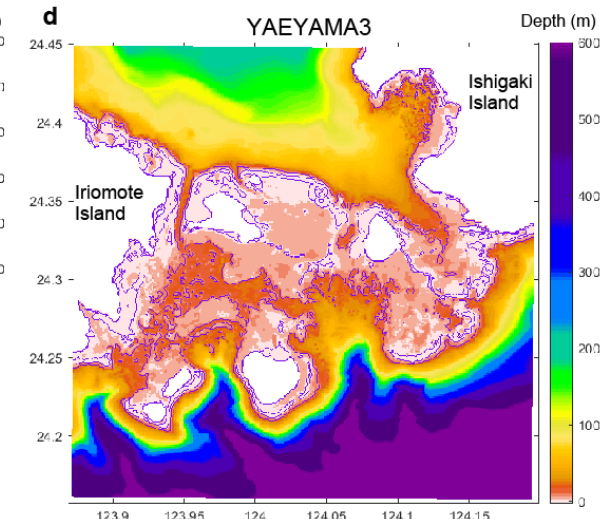
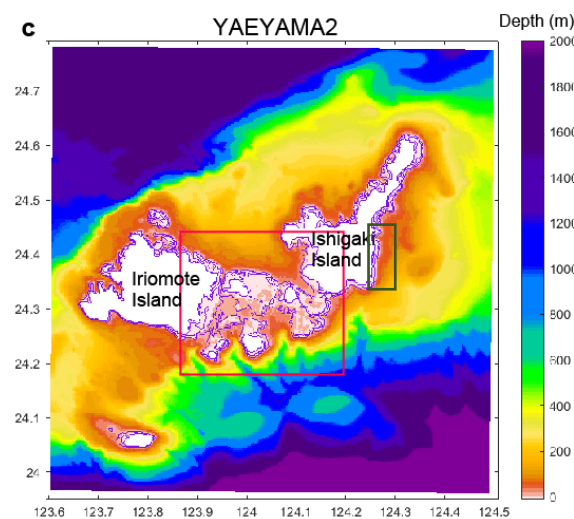
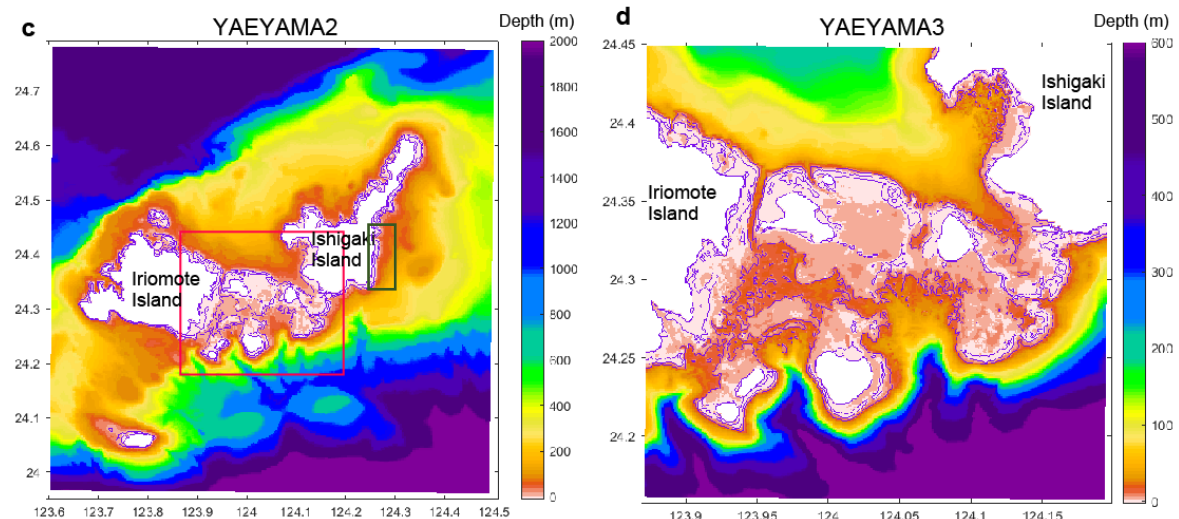
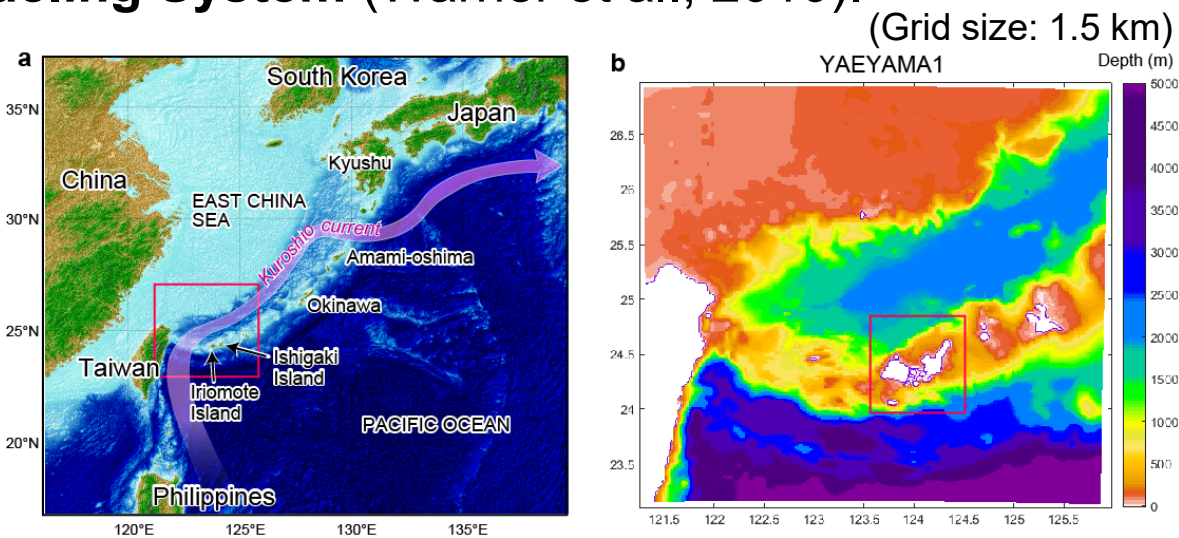
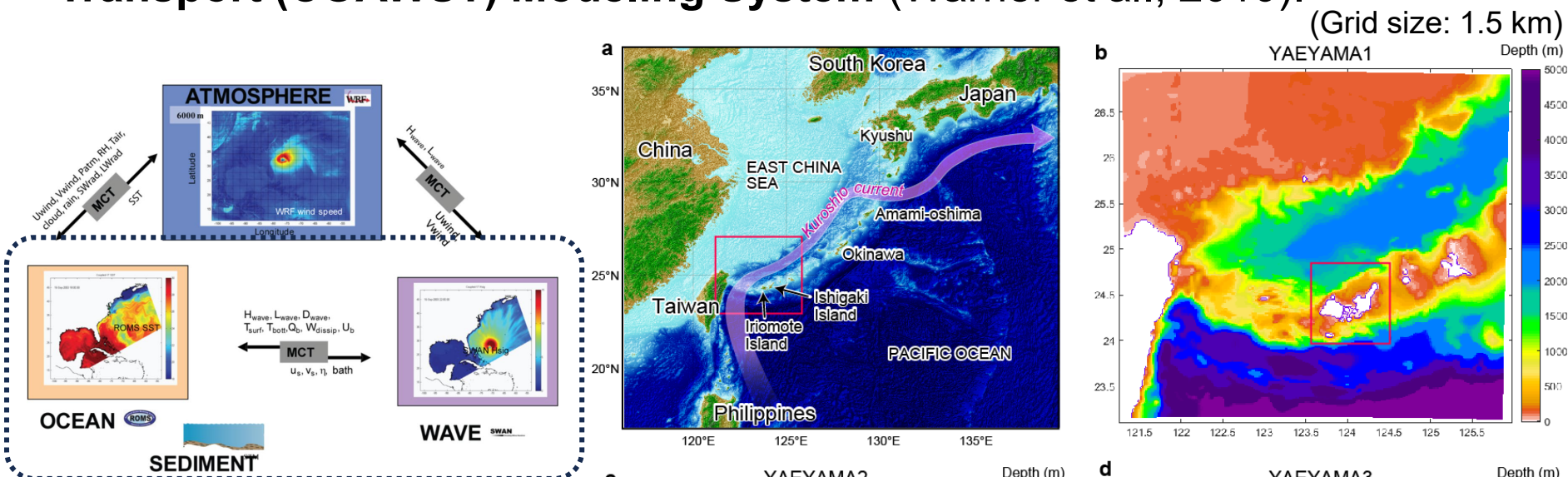
石西礁湖

日本で唯一の礁湖であり、
日本における最大のサンゴ礁域



Ocean Modeling: Sekisei lagoon scale

A multi-nested 3D ocean circulation model for Yaeyama region was developed based on the **Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System** (Warner et al., 2010).

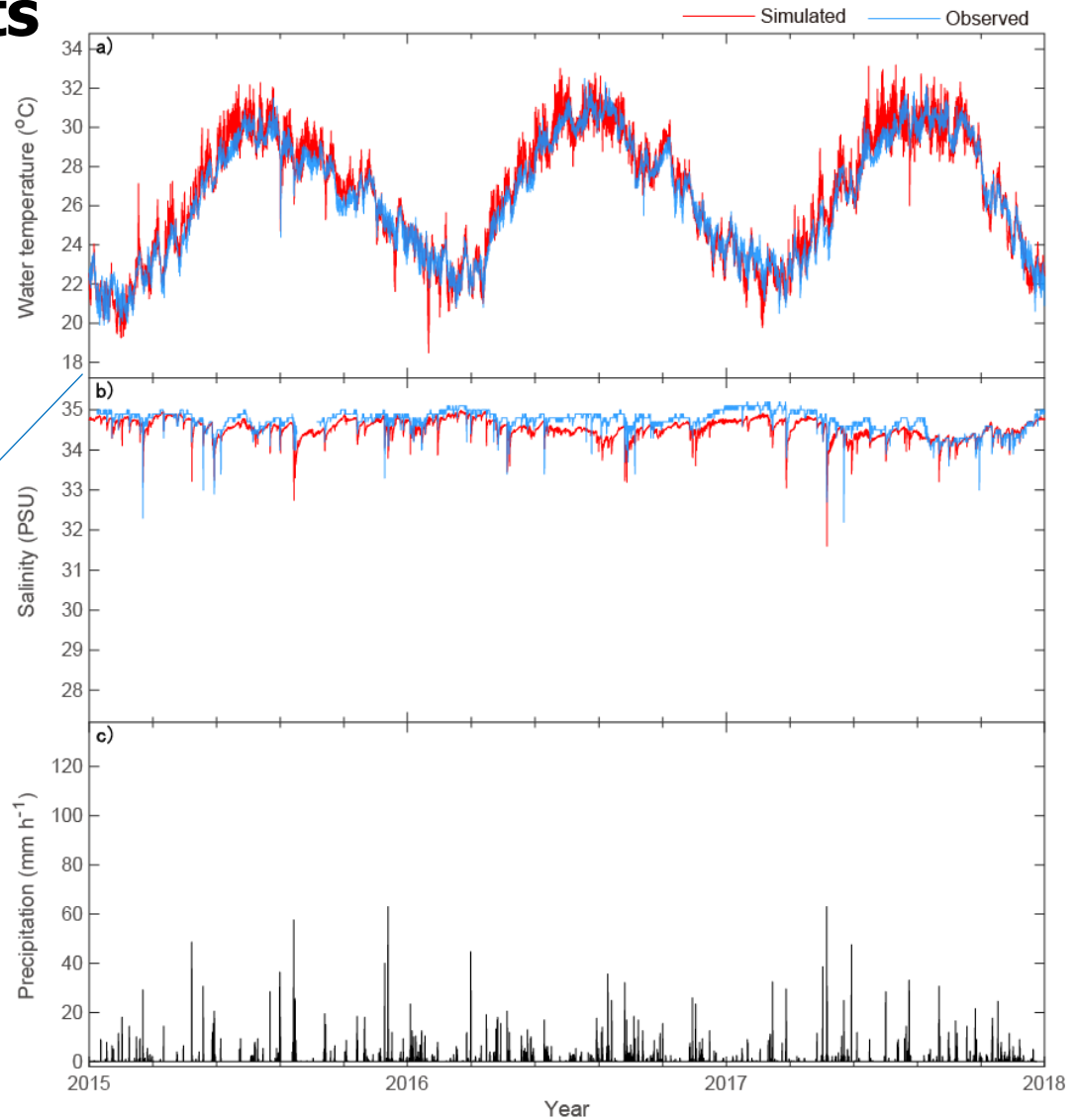
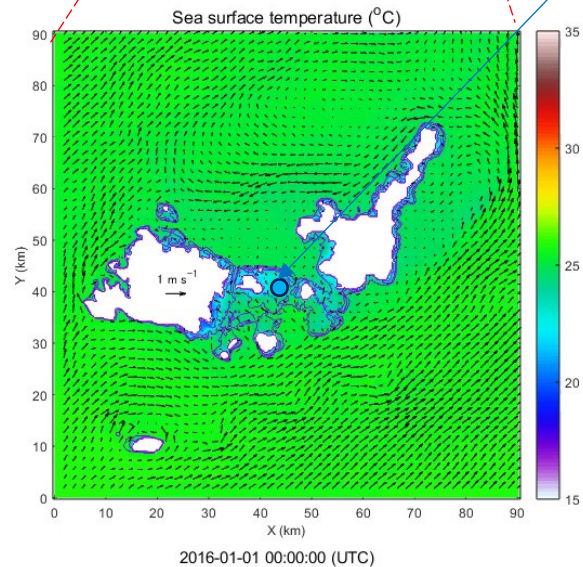
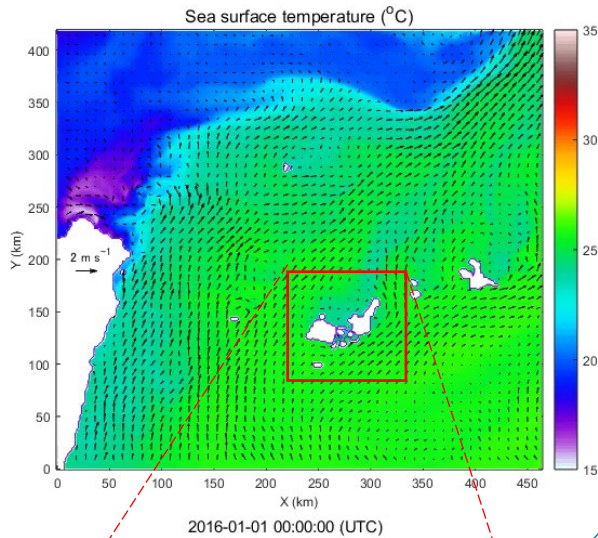


The YAEYAMA1 is nested from Global HYCOM (<https://www.hycom.org/>) / JCOPE-T-DA (Varlamov et al., 2015).

(Grid size: 300 m)

(Grid size: 100 m)

30-year Long-term hindcast simulation for reproducing coral reef environments



(Nakamura, et al., in prep.)

Please see \rightarrow

http://www.nakamulab.mei.titech.ac.jp/yaeyama_hindcast_simulation

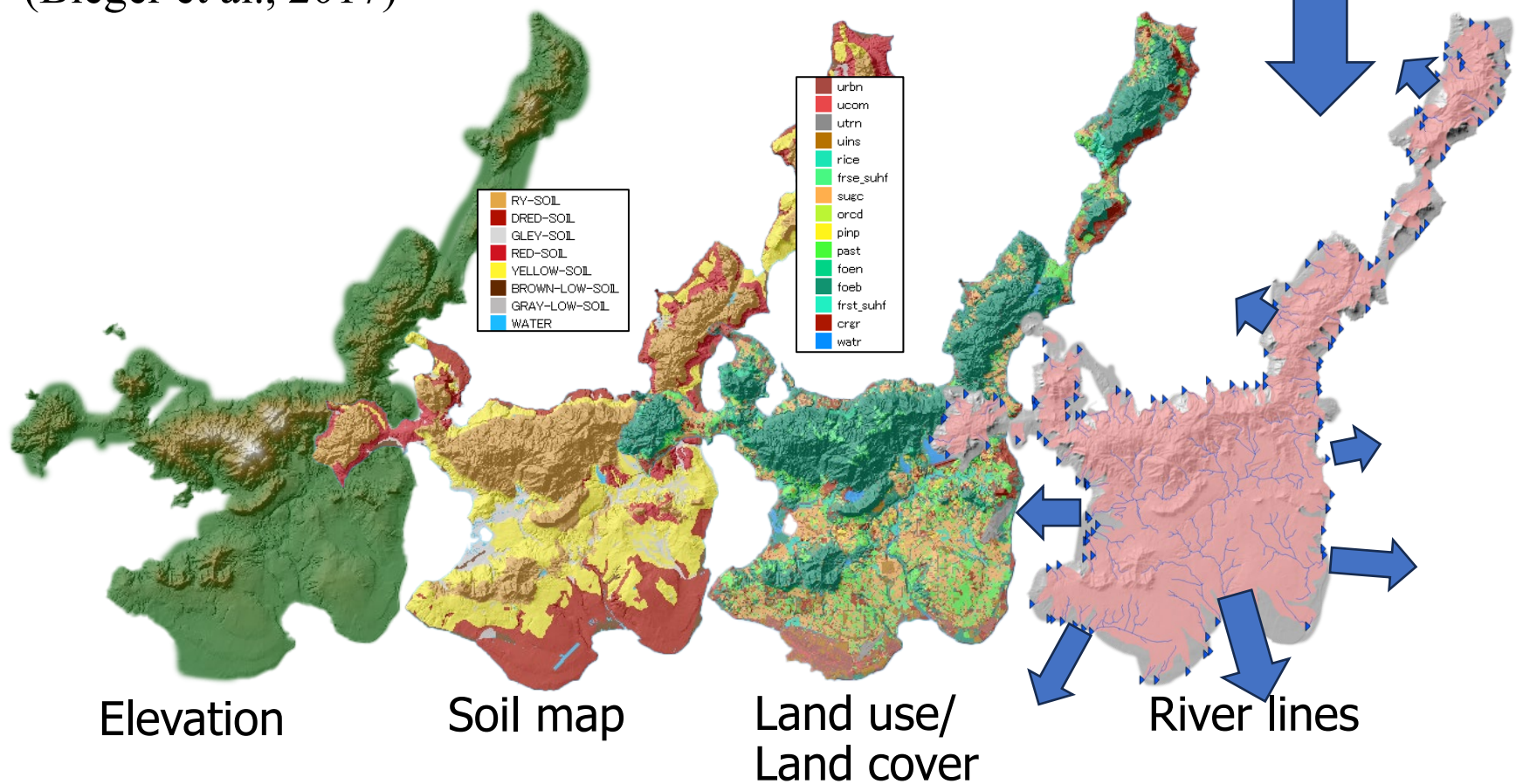


Watershed Modeling



Soil & Water Assessment
Tool+ (SWAT+)

(Bieger et al., 2017)

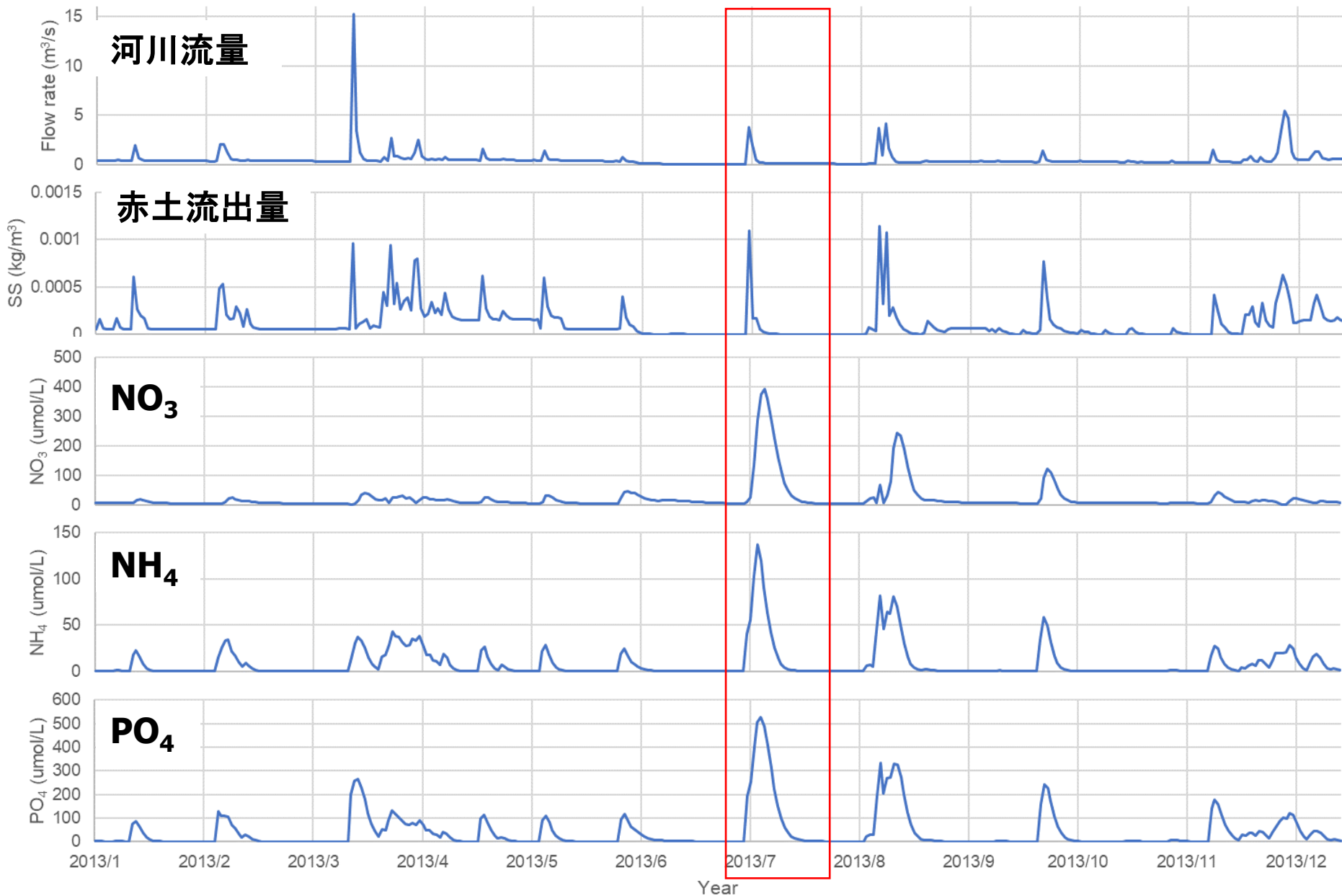


Weather data
(Precipitation, Solar
radiation, Temperature,
Wind, Humidity)

River discharges
(Freshwater, Red soil, Nutrients (NO₃, NH₄, PO₄))

Watershed model (SWAT+) results: Water qualities

Computed Todoroki river (轟川) discharges in 2013



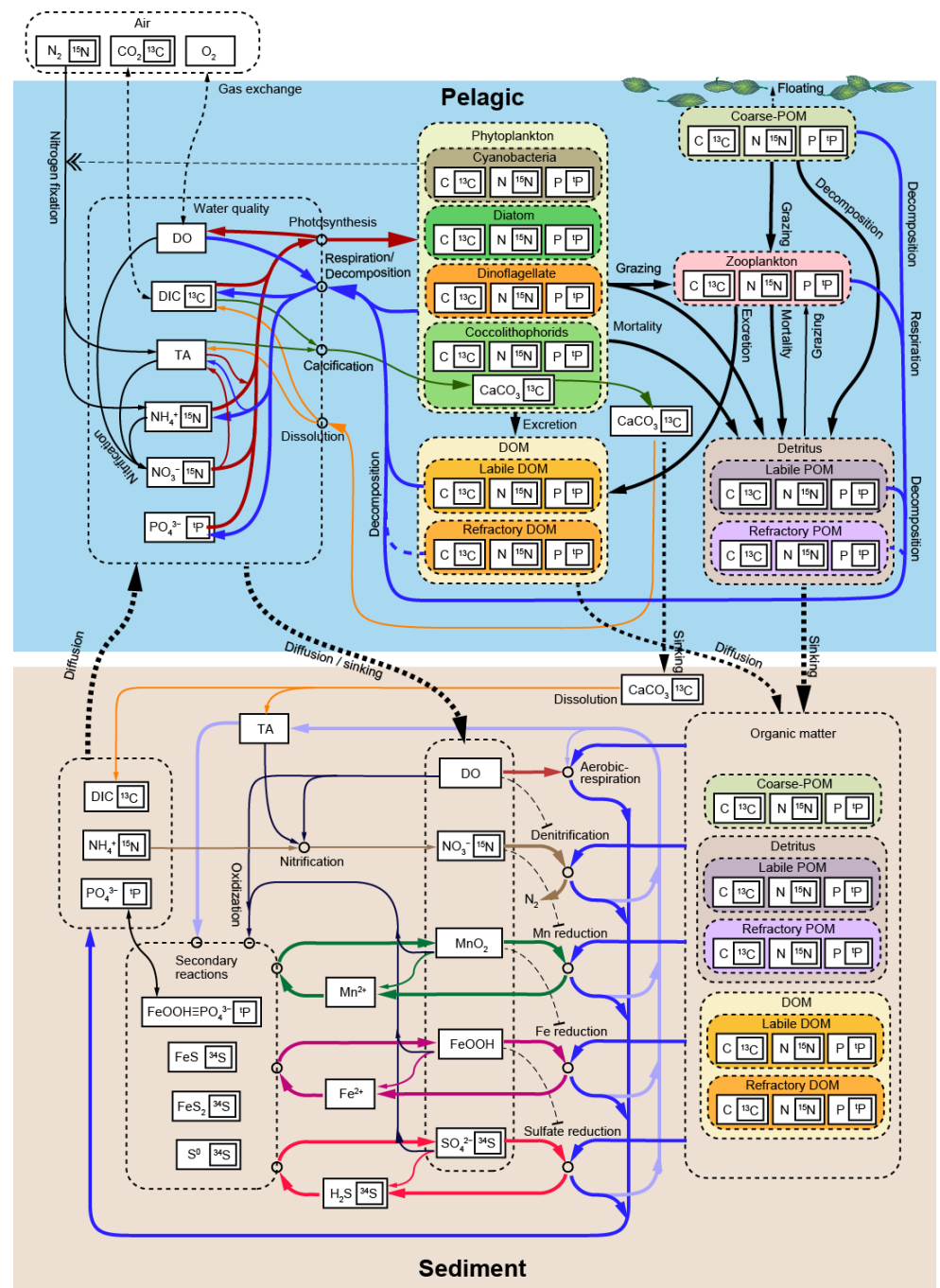
浮遊系-底生系モデル

A Marine Pelagic-Benthic Ecosystem Coupled Model with Element Tracers (Marine CoMET)

- 炭酸系パラメータの組み込み
- 4種類の植物プランクトン
- DOMとPOMの難分解性と易分解性のカテゴリ
- 粗大POM
- 堆積物中の詳細な酸化還元反応
- **C・N同位体/C・N・Pトレーサーの組み込み**
- 底生系ではS同位体/トレーサーも追加

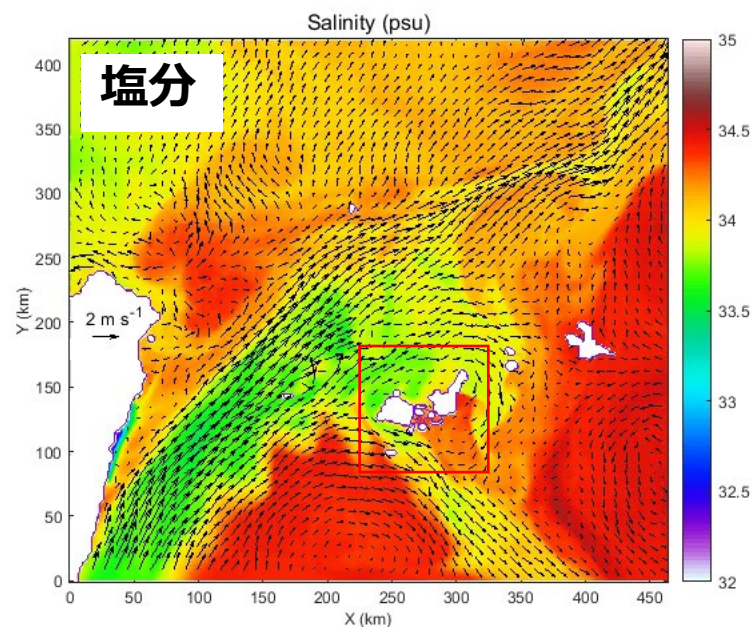
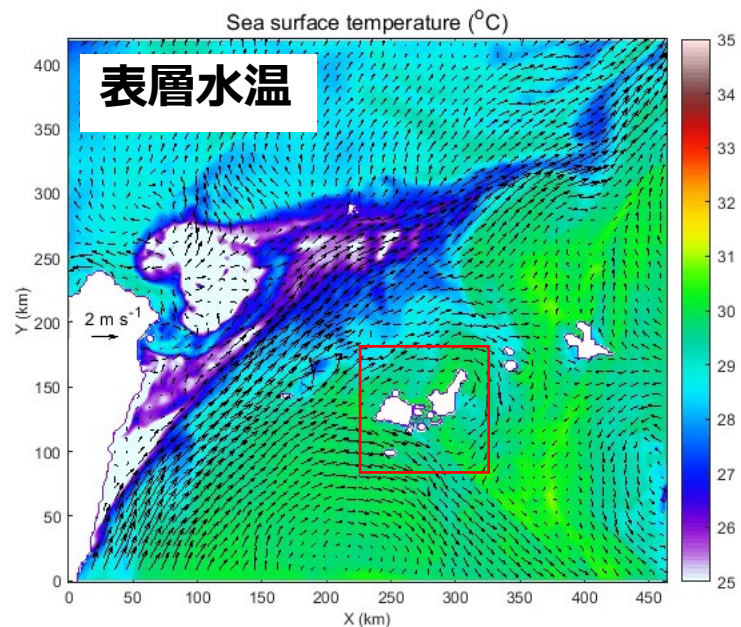
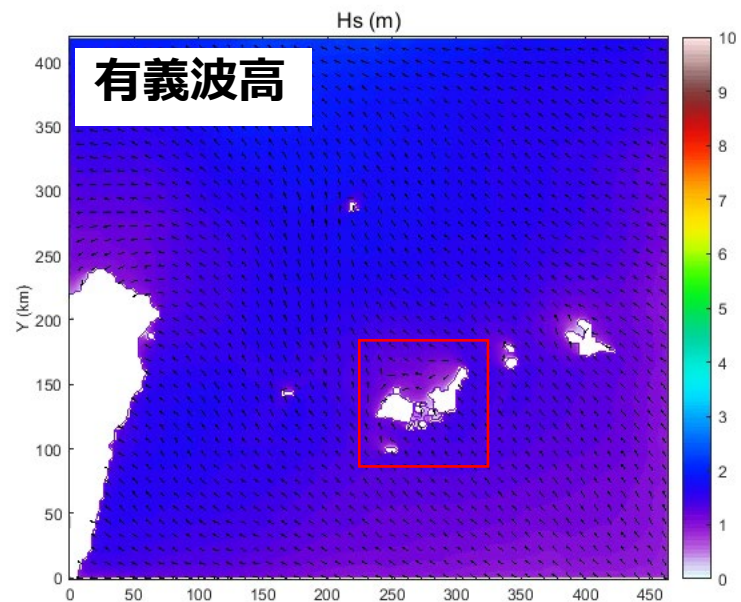
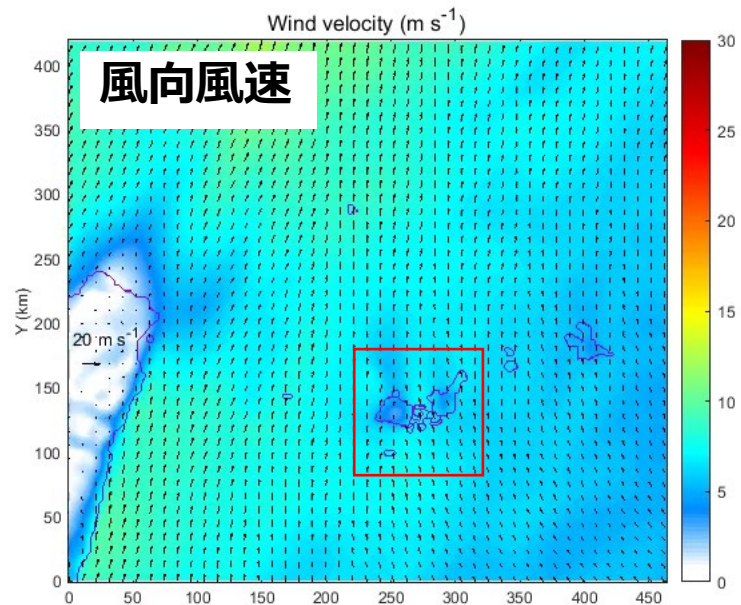


河川などの特定のソースからの炭素、窒素、リンの流転を追跡できるようになった！



(Nakamura et al., in prep.)

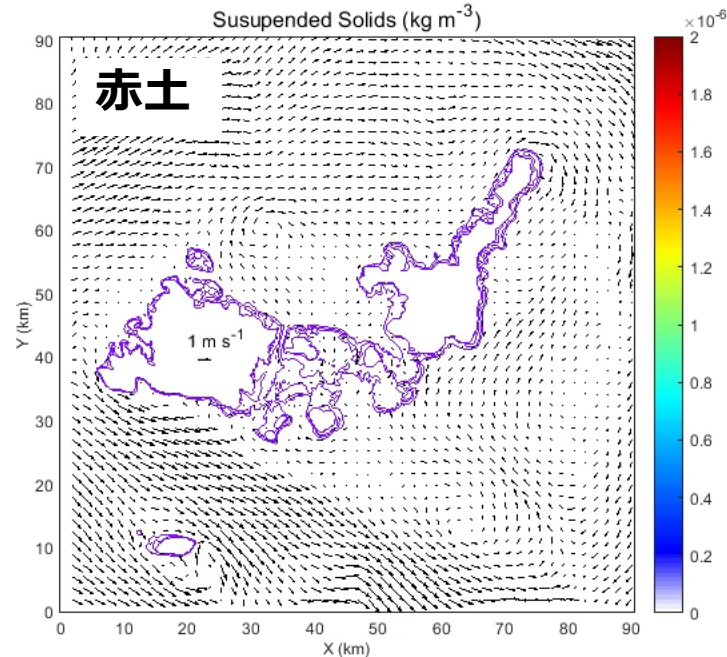
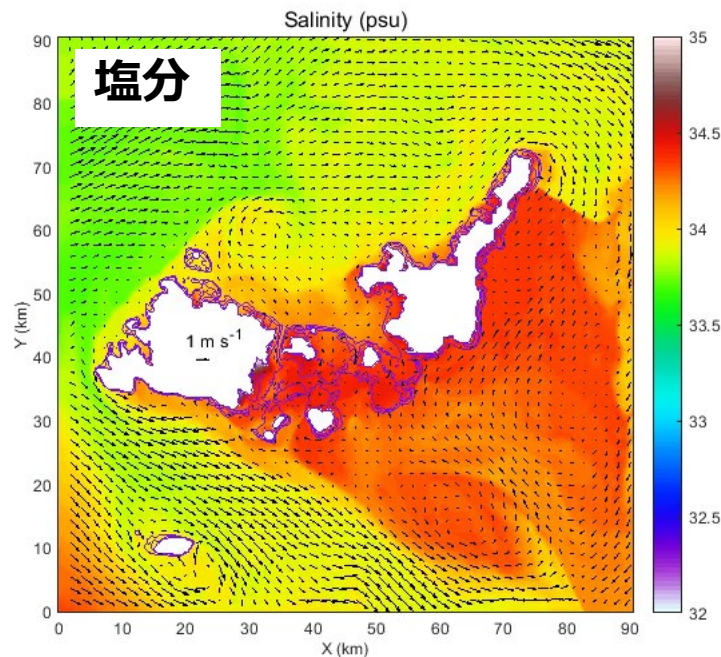
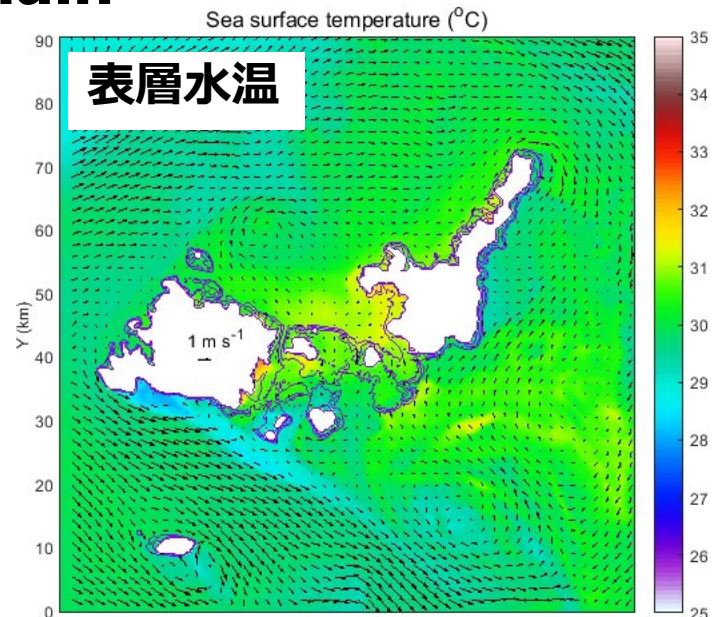
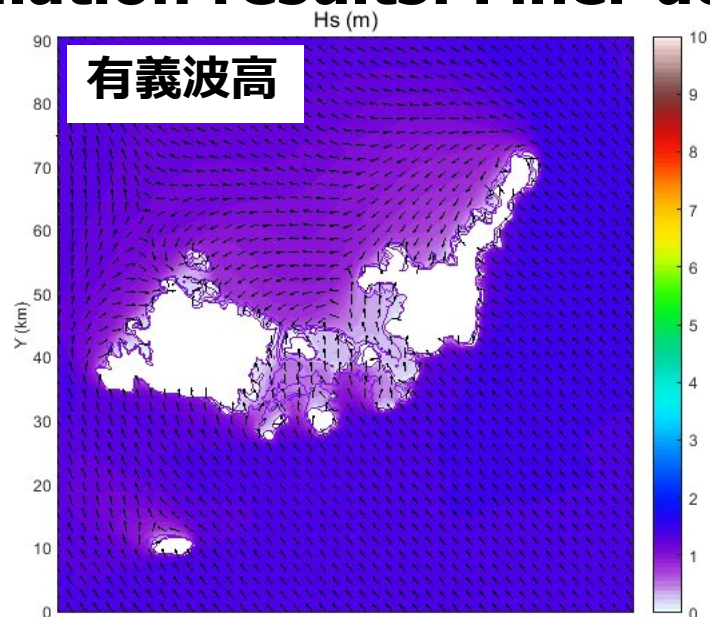
Simulation results: Coarser domain



2013-07-07 00:00:00 (UTC)

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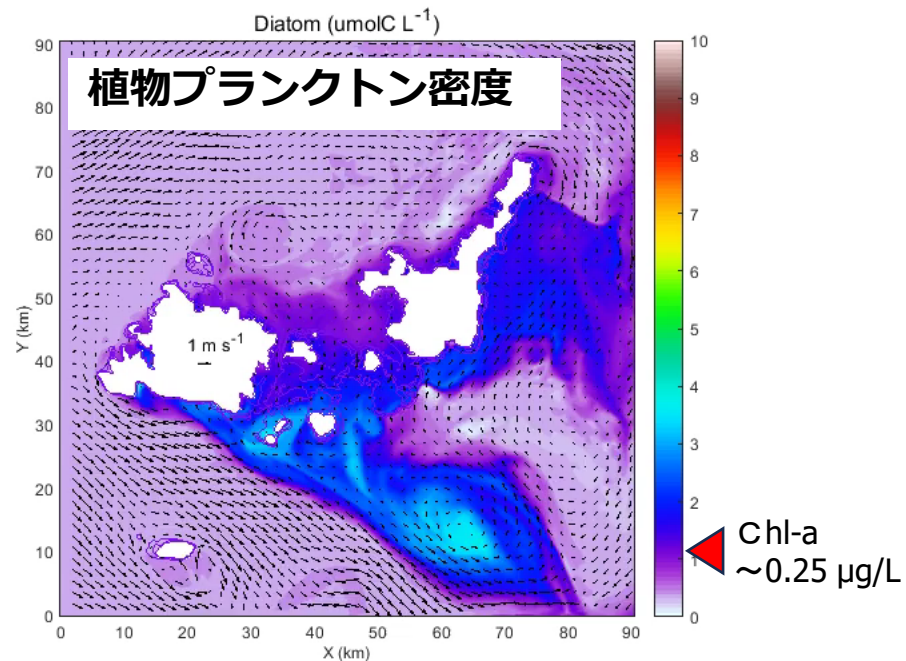
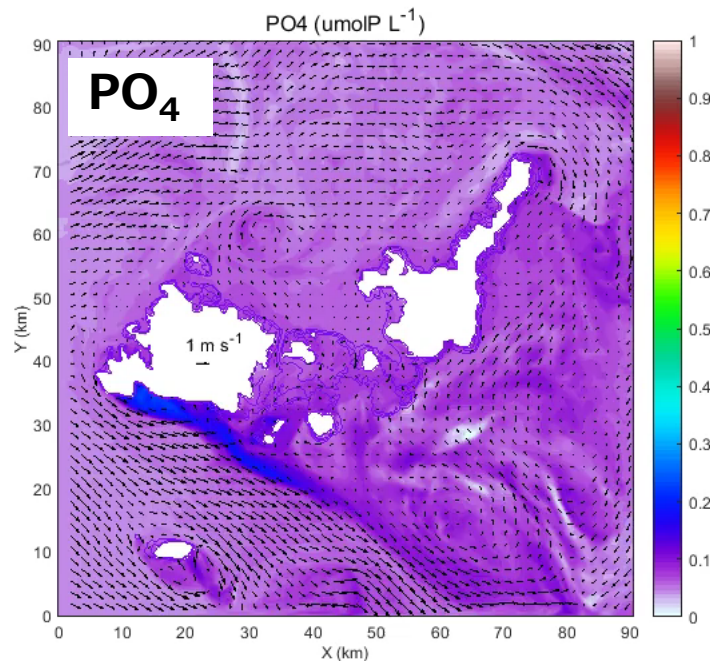
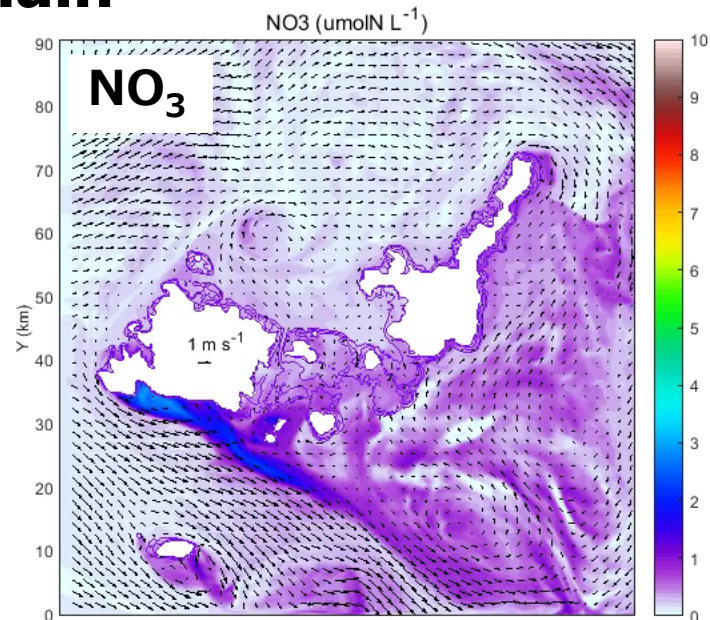
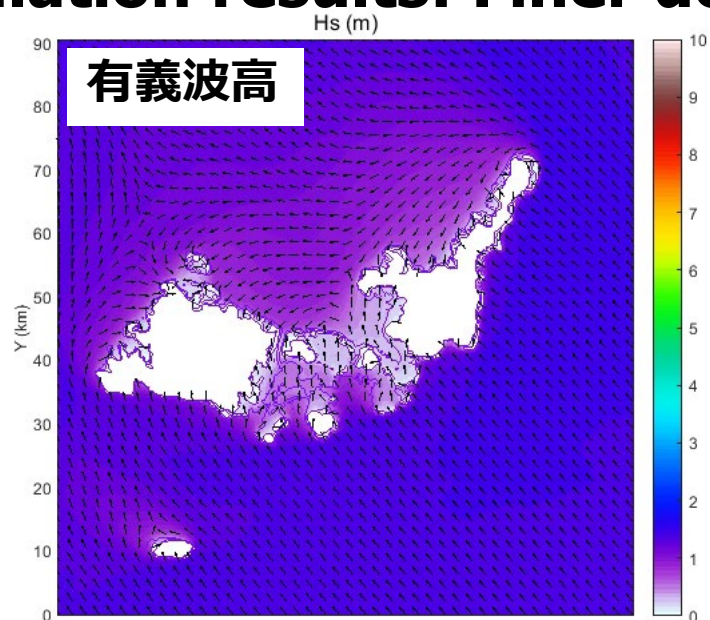
Simulation results: Finer domain



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2013-07-07 00:00:00 (UTC)

Simulation results: Finer domain



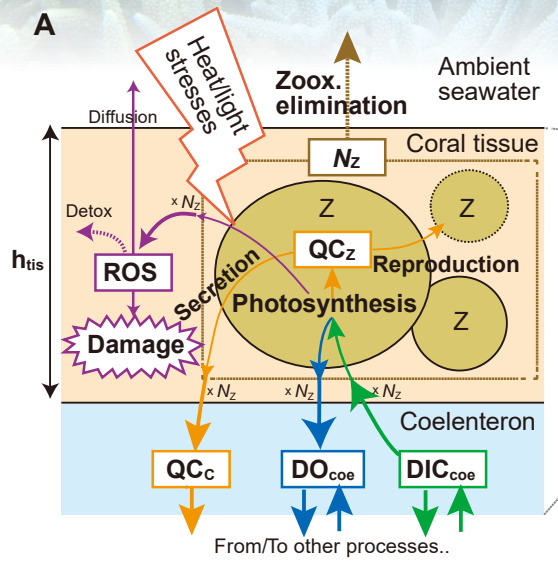
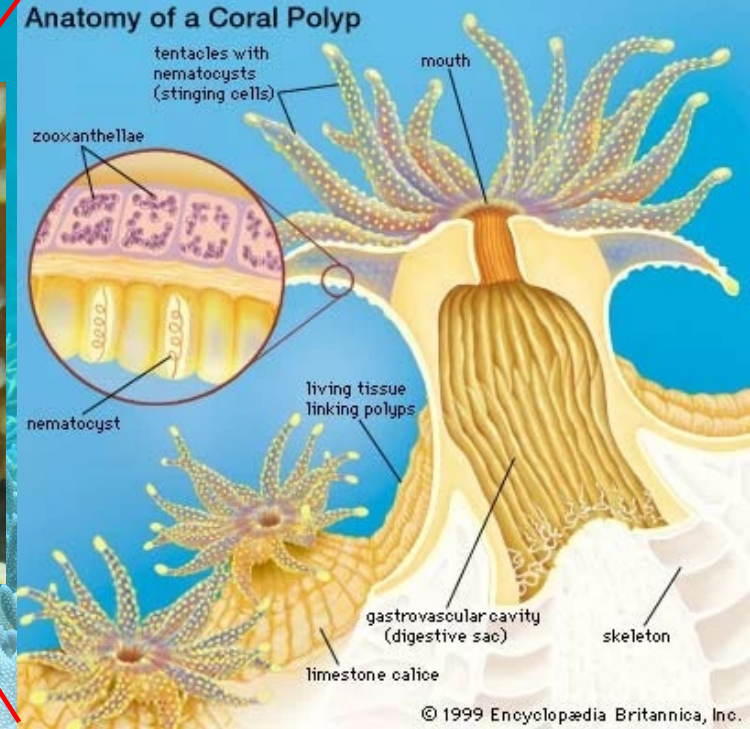
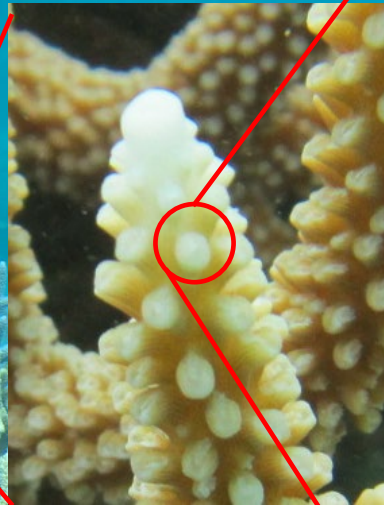
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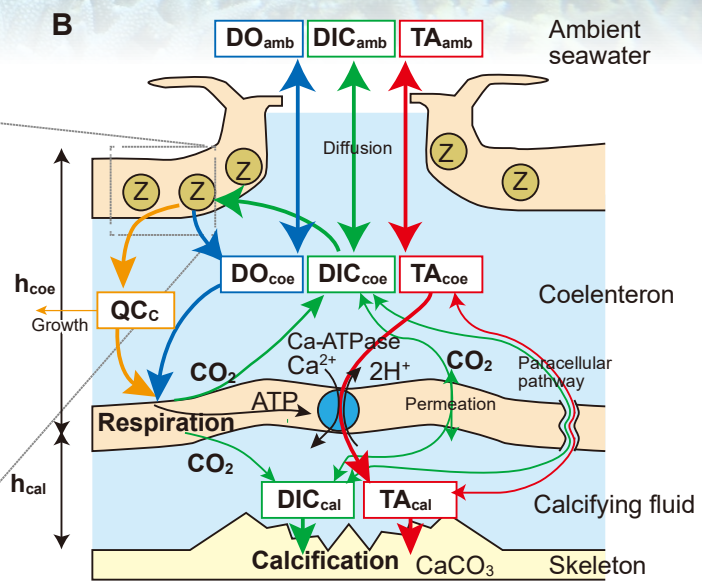
Coral polyp-scale modeling

A coral polyp model, which features well-described coral internal physical, chemical, and physiological processes, has been developed.

The model reproduces well the coral responses to environments, such as **ocean acidification (海洋酸性化)**, temperature (**coral bleaching (サンゴの白化現象)**), flow dependency.

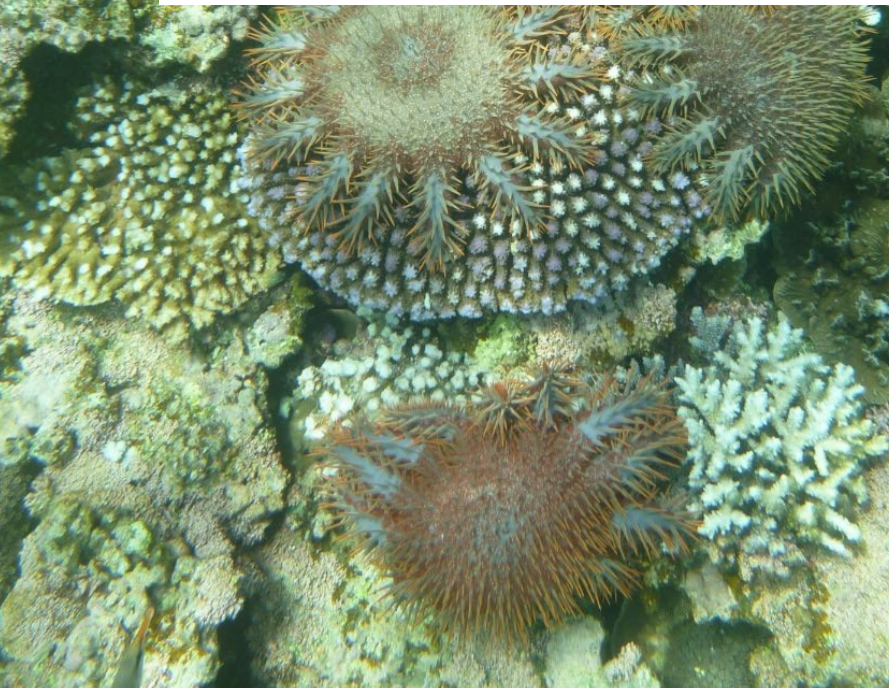


(after Nakamura et al., 2013)





オニヒトデ (COTS) 大量発生の問題



オニヒトデの生活史

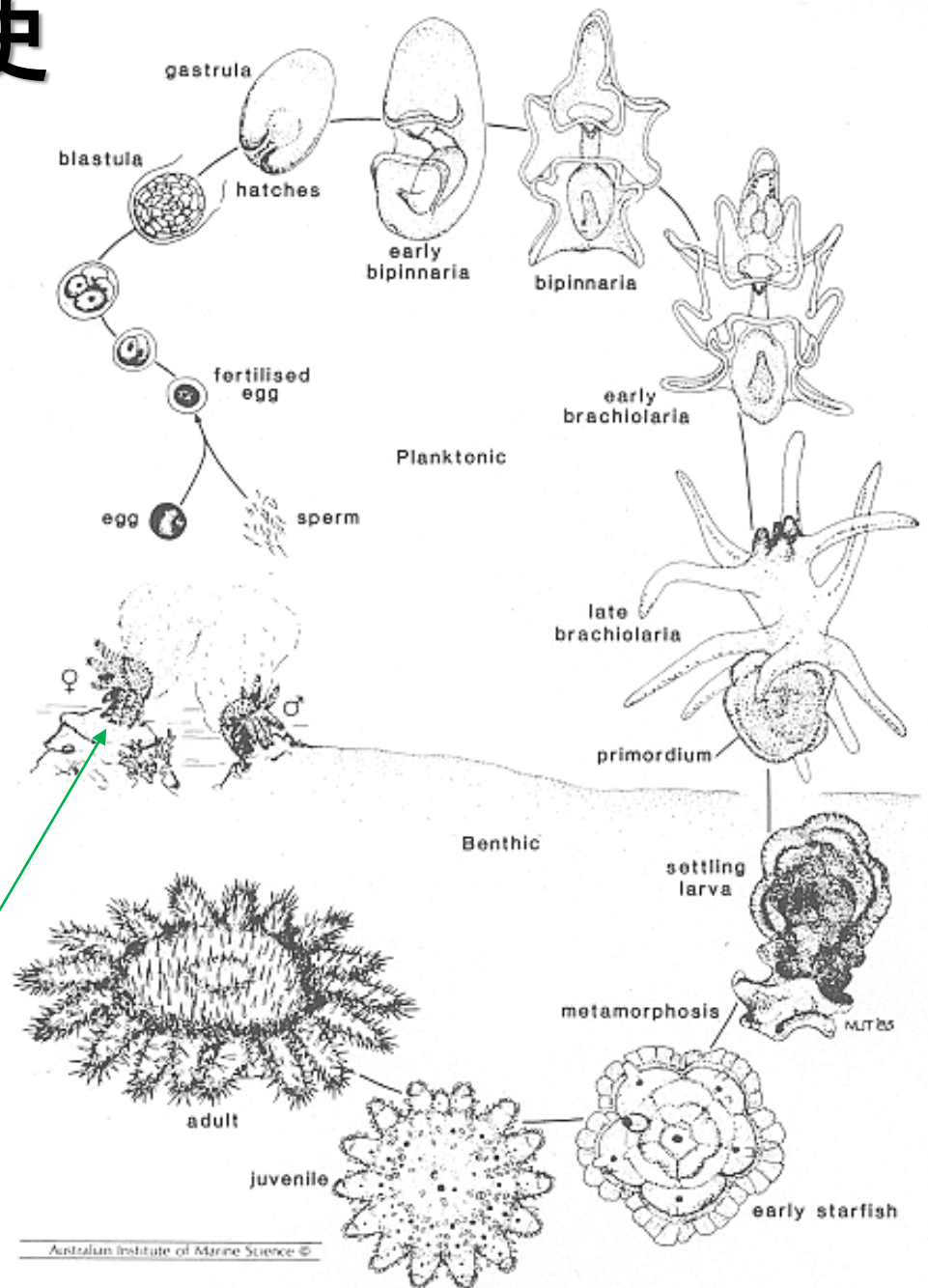
浮遊幼生期:

- ・2~6 週間
- ・植物プランクトン(~2 μ m)を餌とする

着底後:

- ・サンゴ藻食 (< 6 month; ~1 cm in size)
- ・サンゴ食 (>6 month)
- ・約3年で成熟し、次世代を産む (~20 cm in diameter)

オニヒトデは1匹あたり
数千万個(eg. 6千万個)
の卵を放卵する！



(Moran 1988, AIMS)

オニヒトデ (COTS) の大量発生 の 仮説

幼生飢餓説

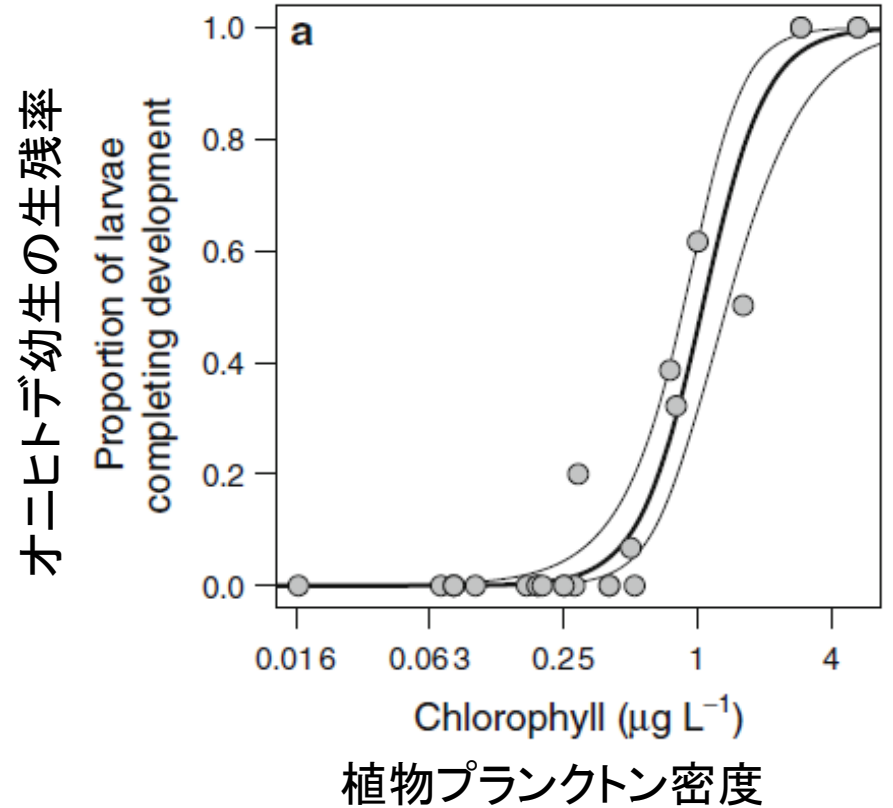
オニヒトデ幼生の生残率は餌となる植物プランクトンの増加に伴い、急激に上昇する。

植物プランクトンは主に陸域起源の硝酸やリン酸などの栄養塩を用いて増殖する



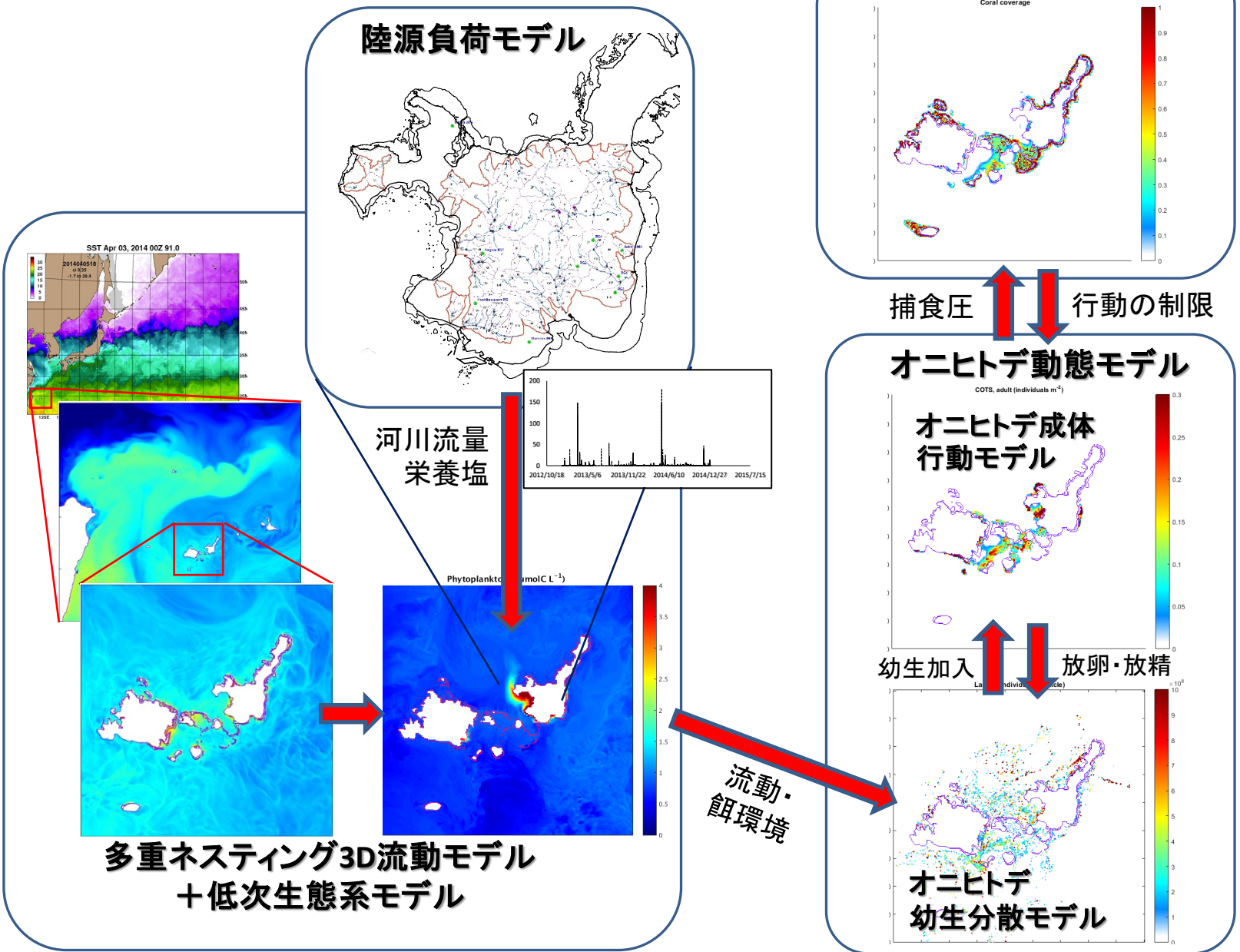
陸からの栄養塩の負荷が増えることでオニヒトデの大量発生が起きやすくなる??

人為的な影響の可能性！



(Fabricius et al., 2010)

Integrated modeling system



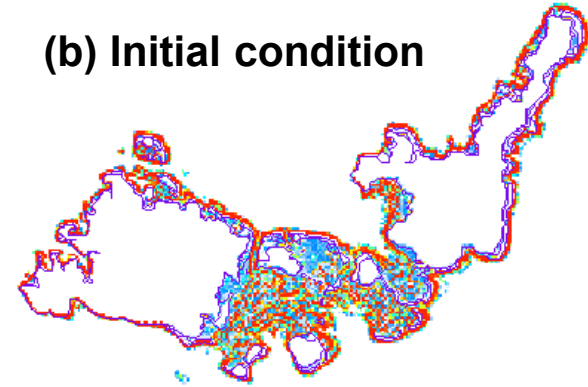
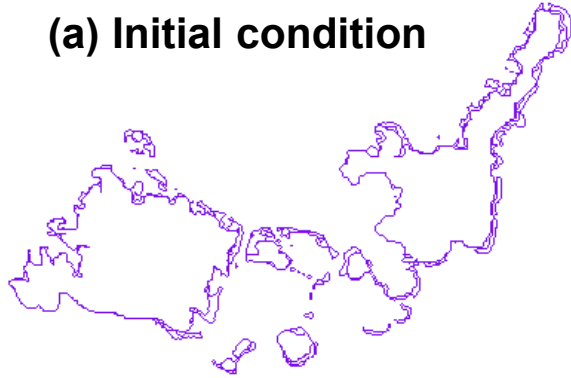
COTS outbreak simulation: scenario analysis

Density of adult COTS (Indiv./m²)

Coral coverage

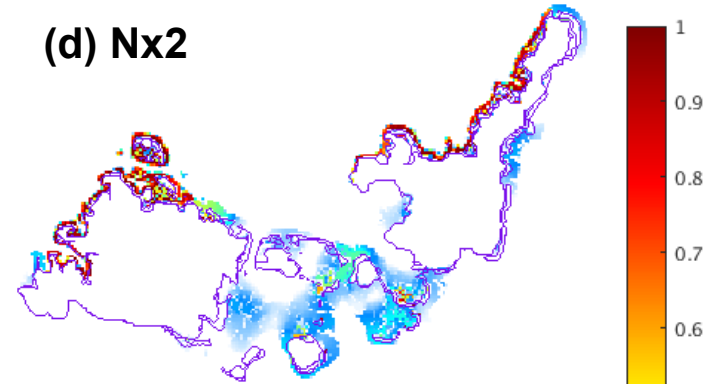
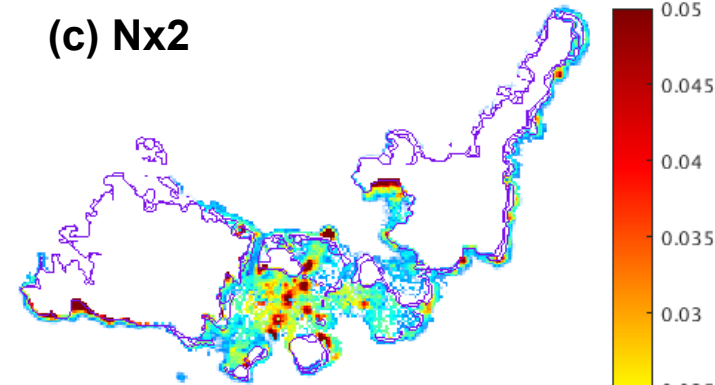
(a) Initial condition

(b) Initial condition



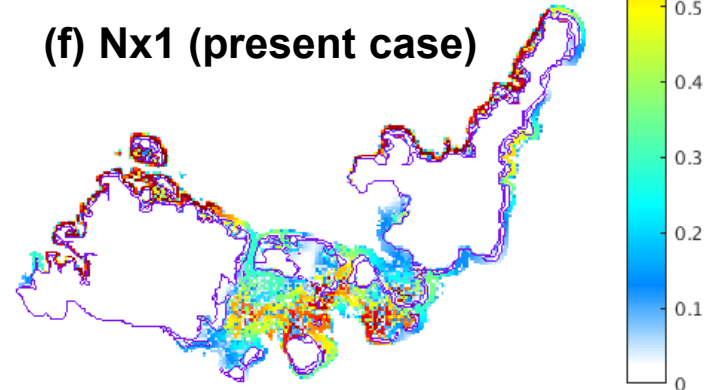
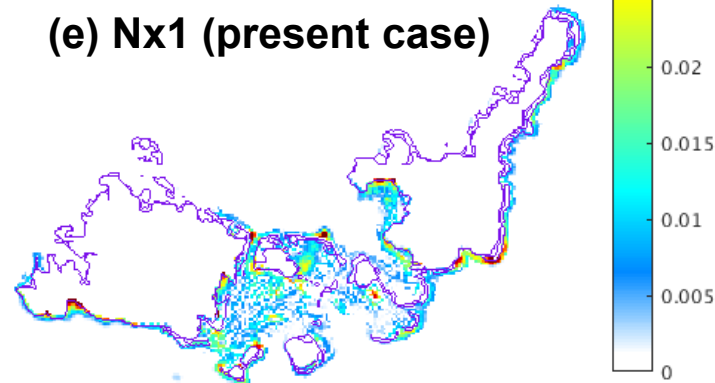
(c) Nx2

(d) Nx2



(e) Nx1 (present case)

(f) Nx1 (present case)



Higher nutrients load



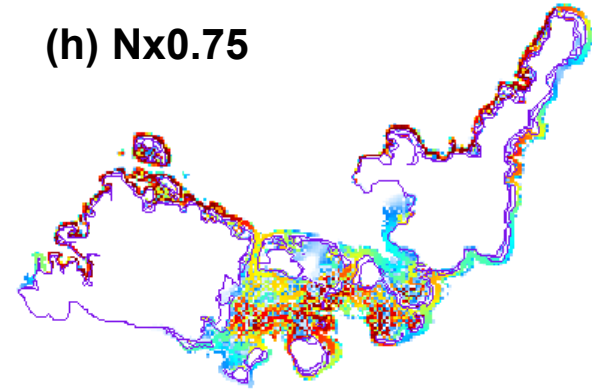
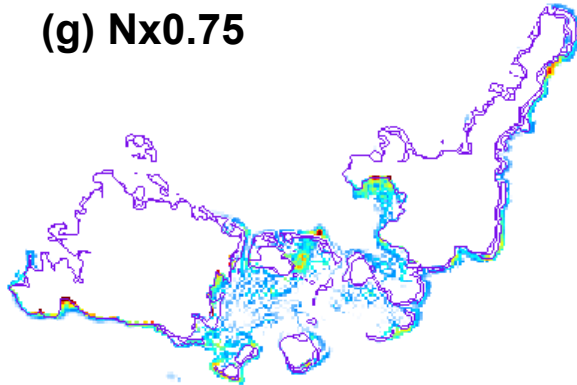
COTS outbreak simulation: scenario analysis

Density of adult COTS (Indiv./m²)

Coral coverage

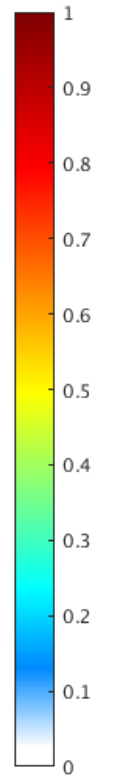
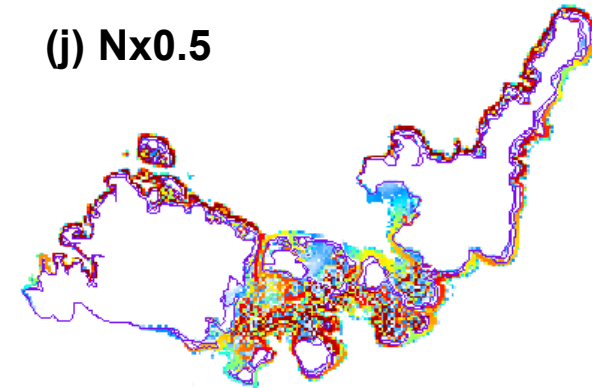
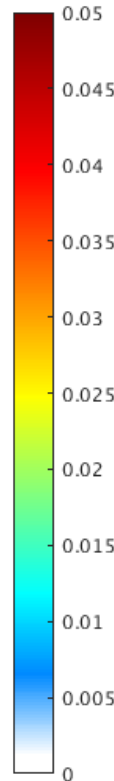
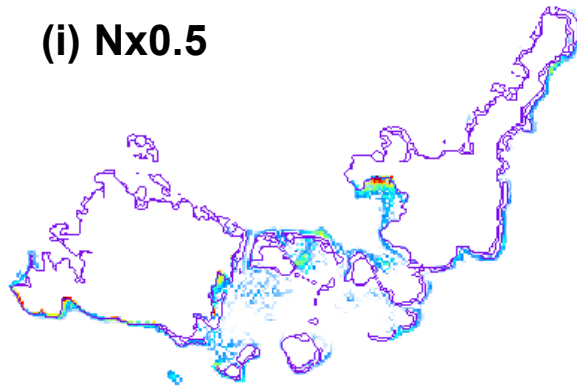
(g) Nx0.75

(h) Nx0.75



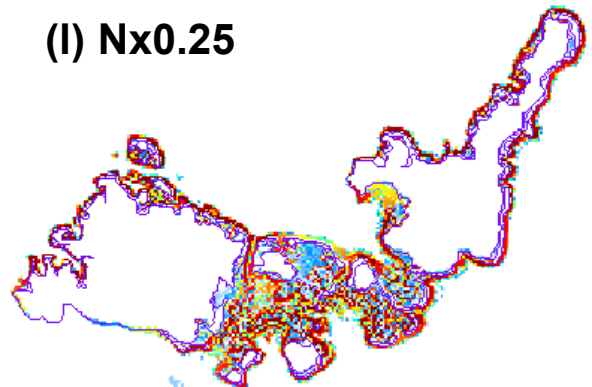
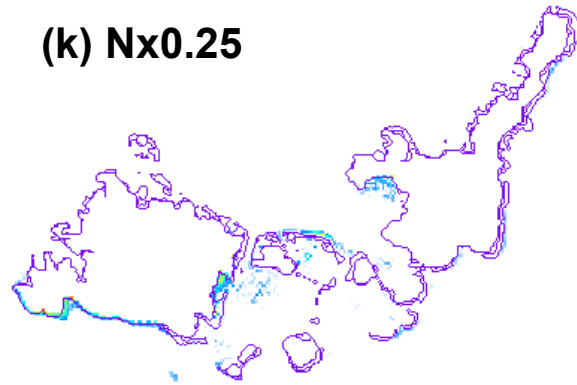
(i) Nx0.5

(j) Nx0.5



(k) Nx0.25

(l) Nx0.25

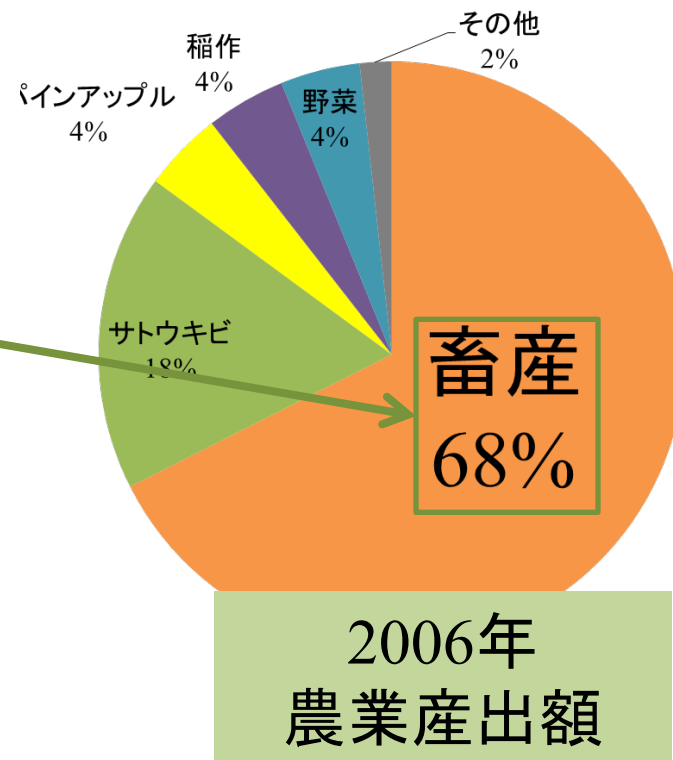
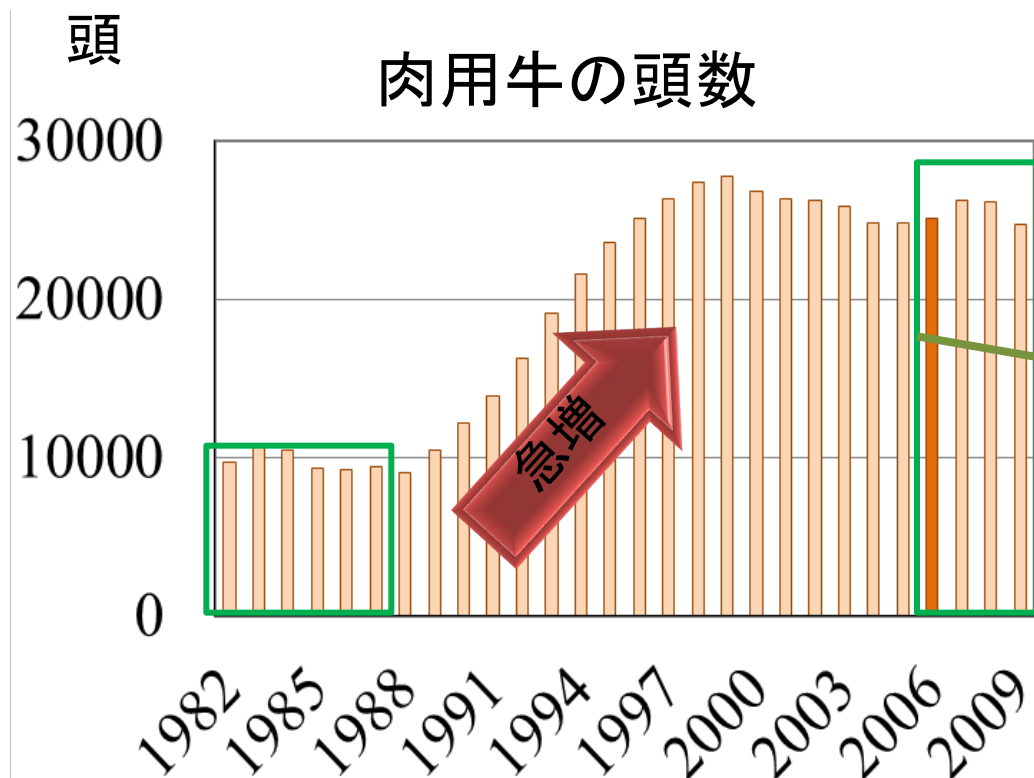


Lower nutrients load

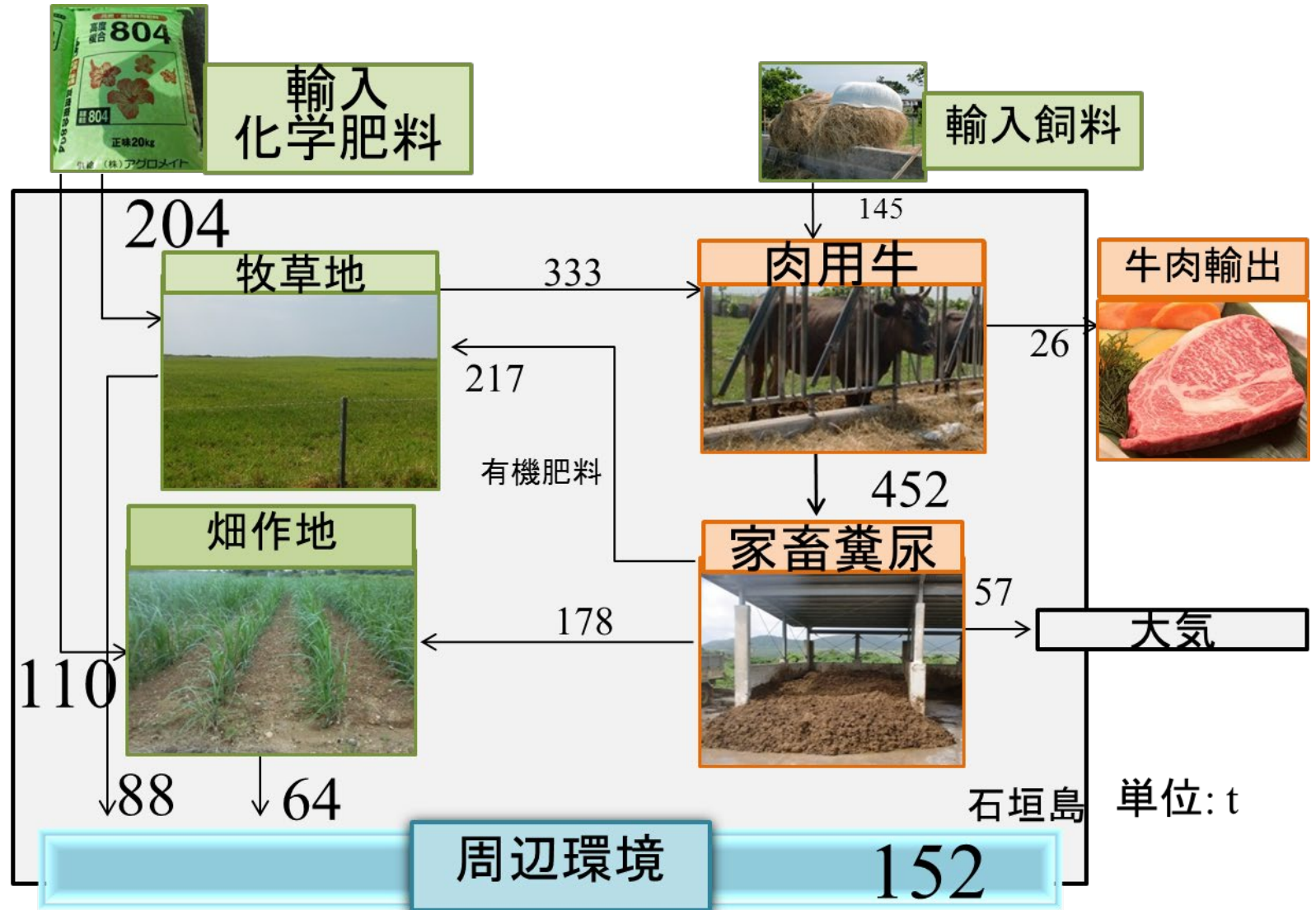
石垣島での畜産業の大きな発展

1990年代に石垣島では肉用牛が2.5倍に急増した。

畜産業は今や農業産出額の多くを占め、石垣島は今や「**畜産の島**」になっている。

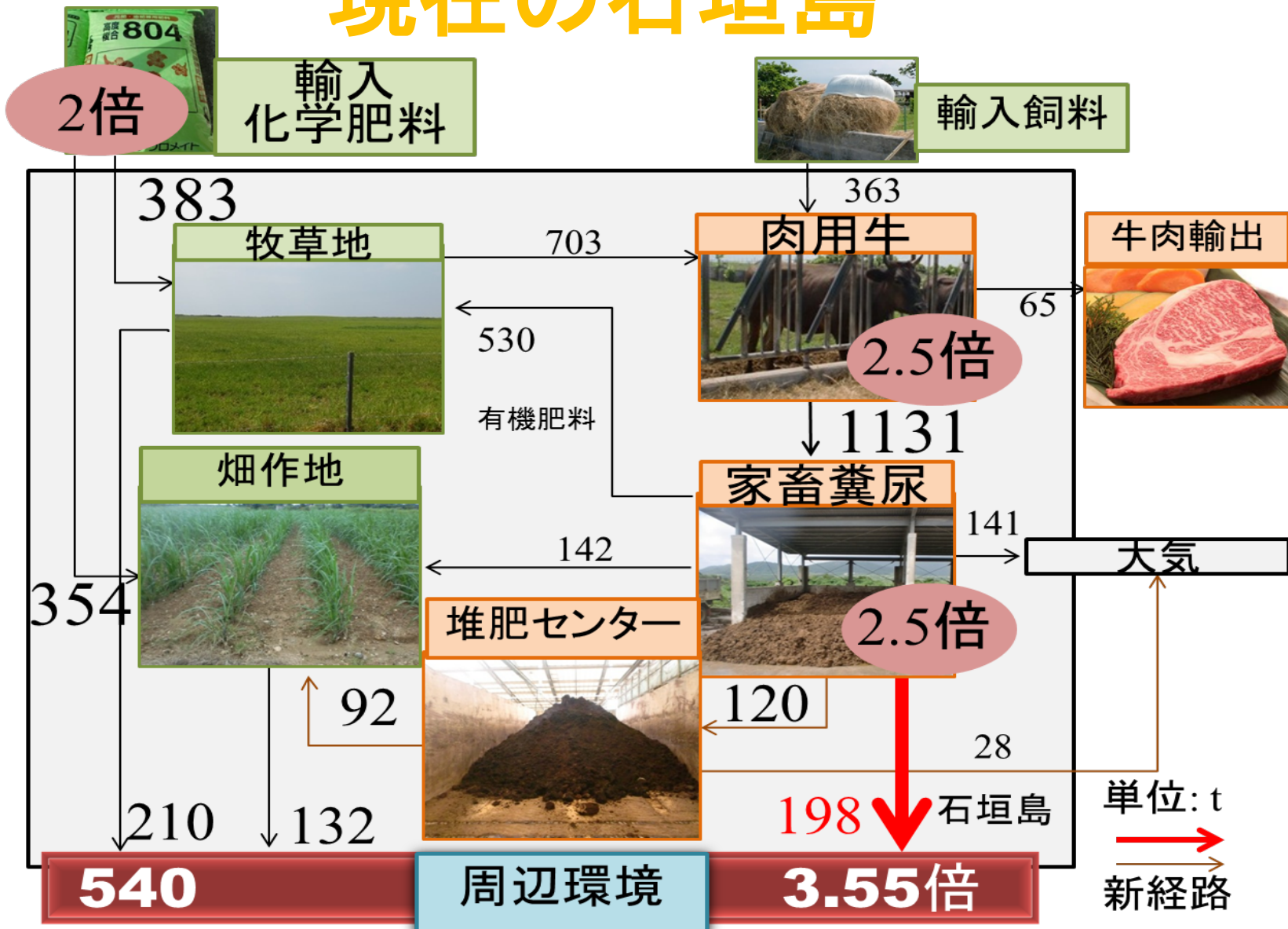


肉用牛急増以前の石垣島



小規模な畜産とサトウキビの兼業農家が多く、糞尿は自身や近隣の農家で有効に使用されるリサイクル構造が成立していた。

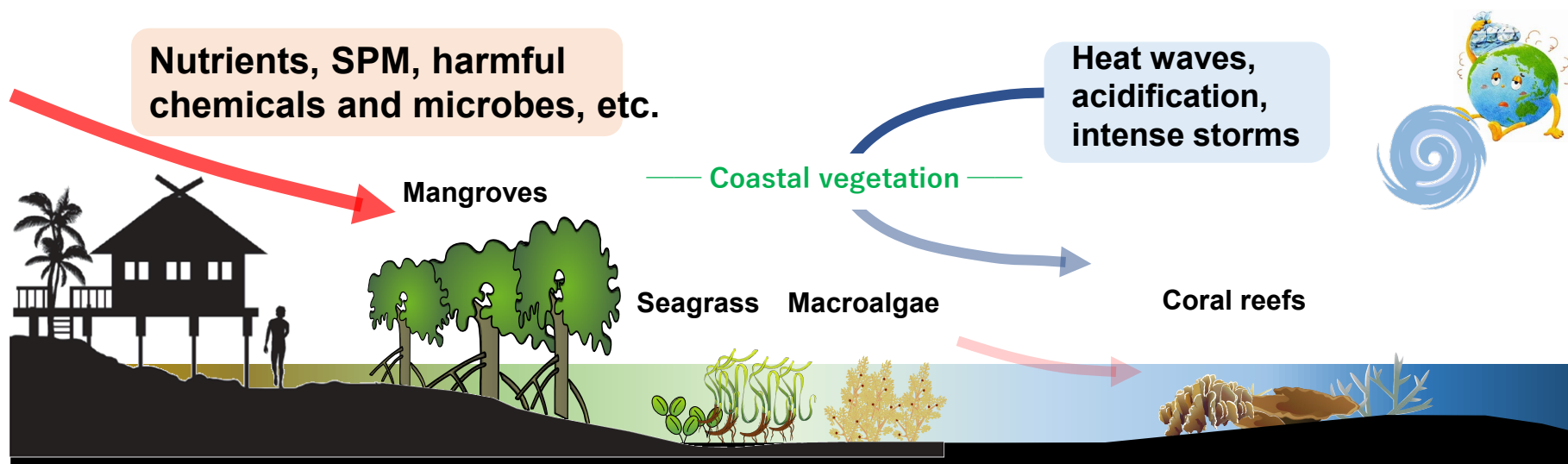
現在の石垣島

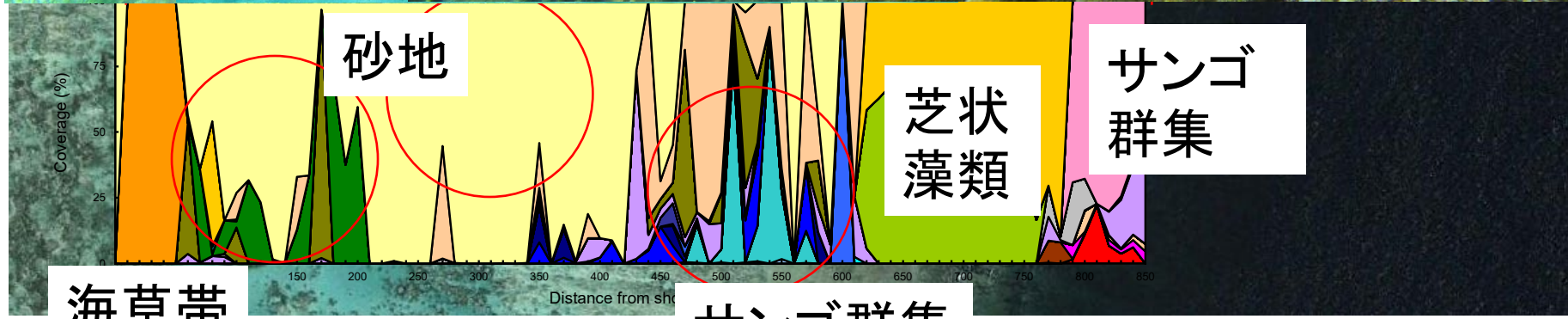
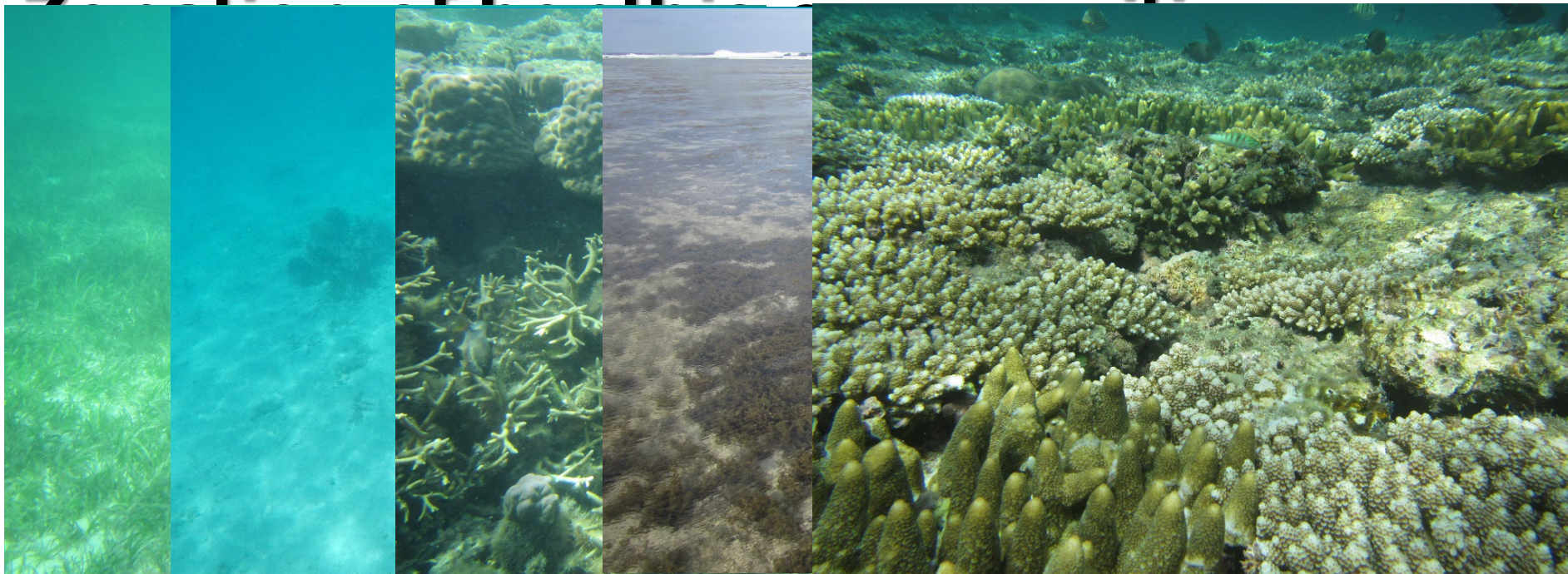


頭数の急増に対応することができず、農家の中で処理しきれずに余ってしまった糞尿が作物に**利用されず**に**流出する経路**が**顕著**になった。

流動場生態系モデルと流域負荷モデルを用いたサンゴ礁保全・再生における緩衝植生帯の効果に関するシナリオ解析

Development of nature-based solutions for conservation and restoration of coral reefs





海草帯

砂地

芝状藻類

サンゴ群集

サンゴ群集

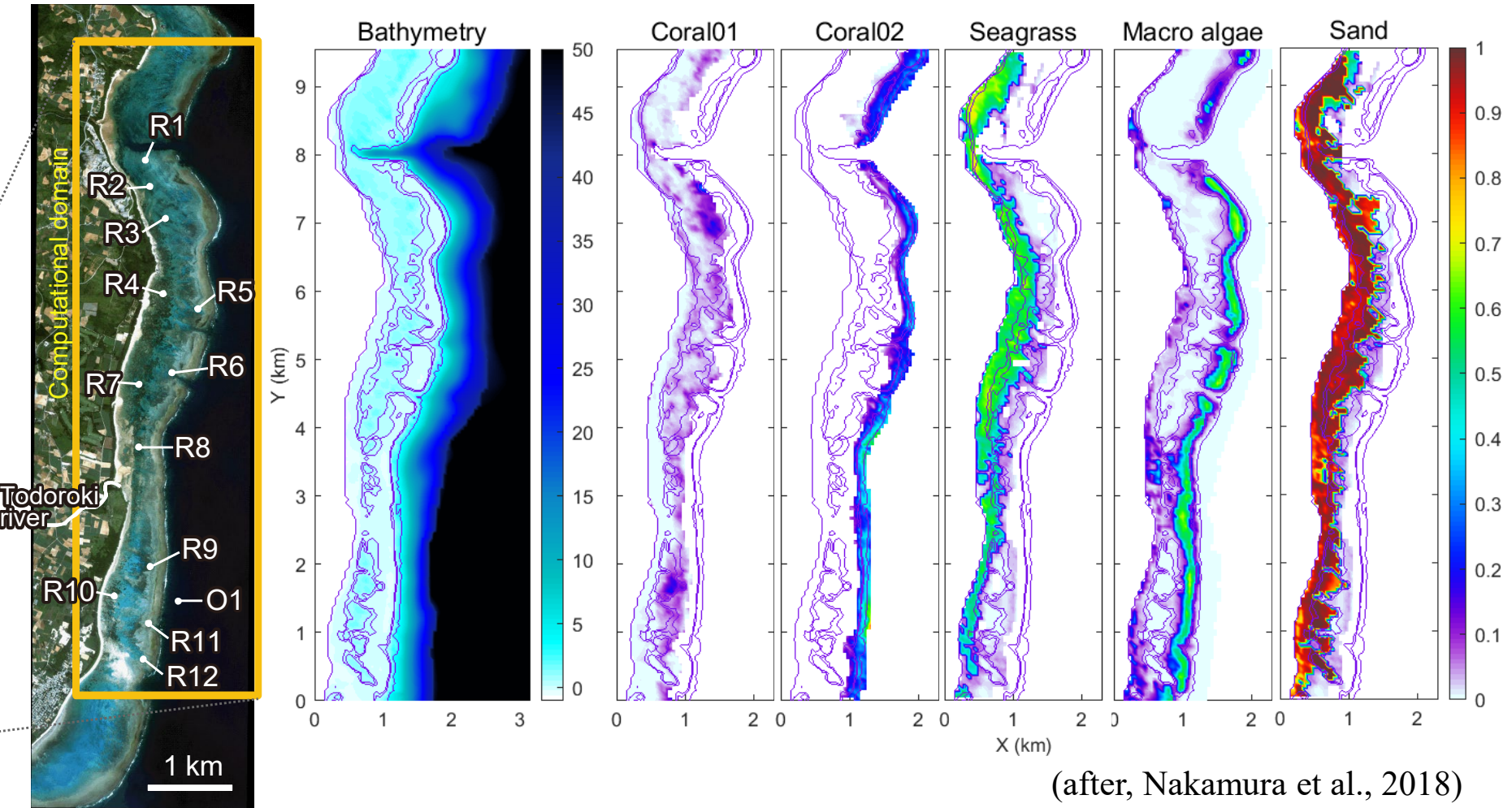
- | | | | |
|-----------------------|-------------------------------|----------------------|------------------------|
| Acropora monticulosa1 | Acropora digitifera | Acropora hyacinthus | Acropora microphthalma |
| Acropora muricata | Acropora carduus | Porites cylindrica | Pavona cactus |
| Pavona venosa | Other corals | Soft coral | Algal lawn |
| Algal turf | Coralline algae (live & dead) | Saeagrass | Other Algae |
| Reef rock (old) | Reef rock (mount) | Reef rock (pavement) | Sand & gravel |

Coral reef communities have clear habitat zone paralleled to shoreline.

(Nakamura & Nakamori 2009)

Computational domain (Shiraho reef)

This modeling system was applied to a coral reef ecosystem on Shiraho fringing reef, Ishigaki Island, Japan.



Shallow water depth and benthic coverage are derived from satellite image analysis.

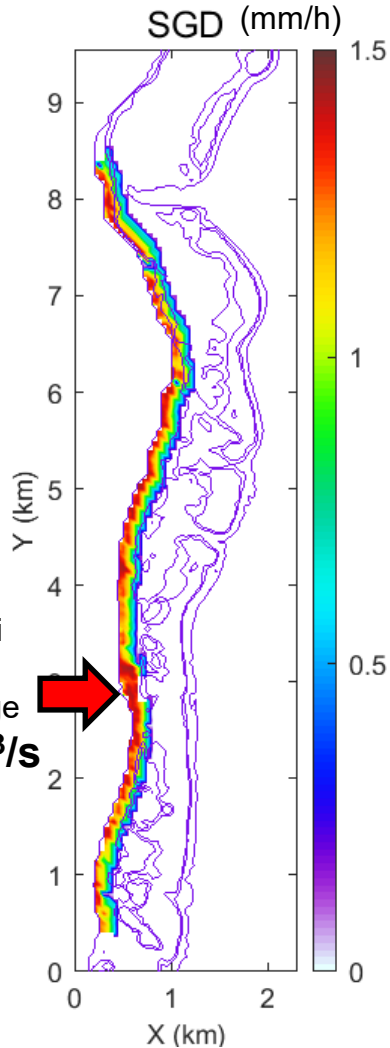
Simulation settings

Constant river and
Submarine groundwater
discharges

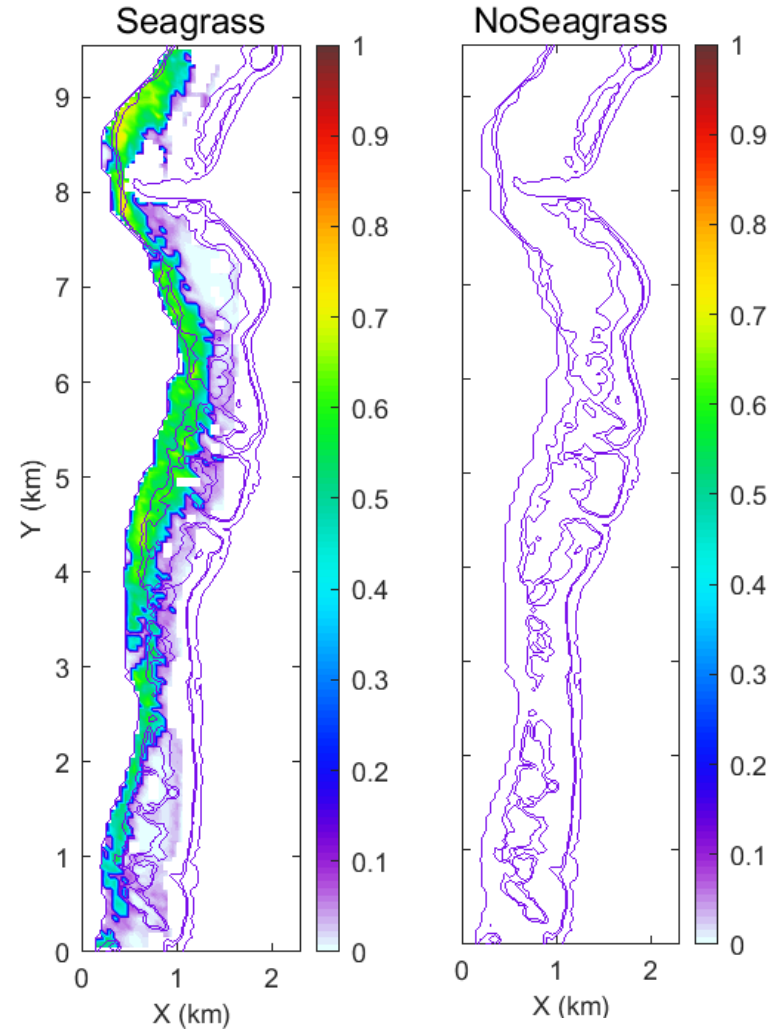
Seagrass coverages

海草有
Case 1

海草無
Case 2



| | Todoroki | SGD |
|--------------------------|----------|------|
| NO ₃ (μmol/L) | 150 | 260 |
| NH ₄ (μmol/L) | 1.5 | 0.1 |
| PO ₄ (μmol/L) | 1.6 | 0.25 |
| SS (kg/m ³) | 0.1 | 0 |
| DIC (μmol/kg) | 3000 | 3400 |
| TA (μmol/kg) | 3000 | 3400 |



海草帯による波浪/流動場への影響

有義波高

Case 1

Case 2

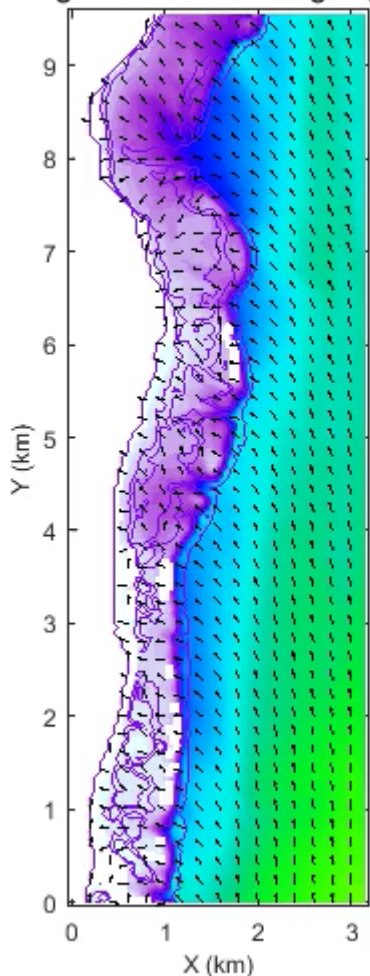
底面せん断応力

(波による往復運動+平均流)

Case 1

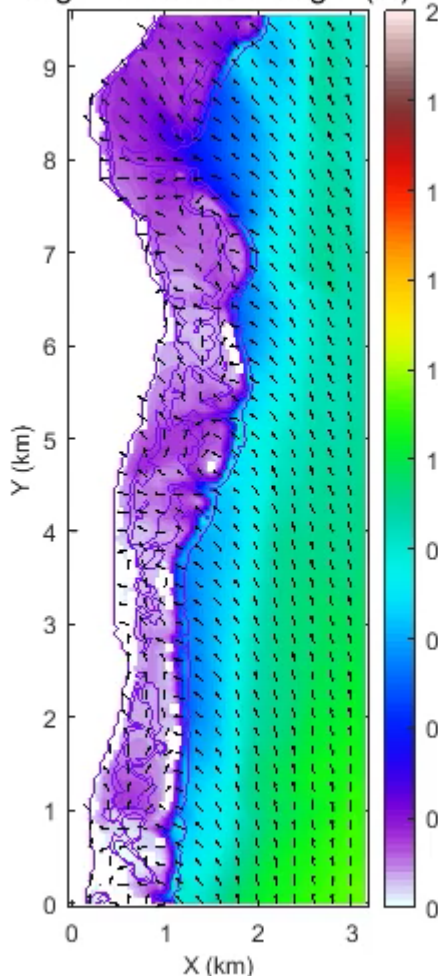
Case 2

Significant wave height (



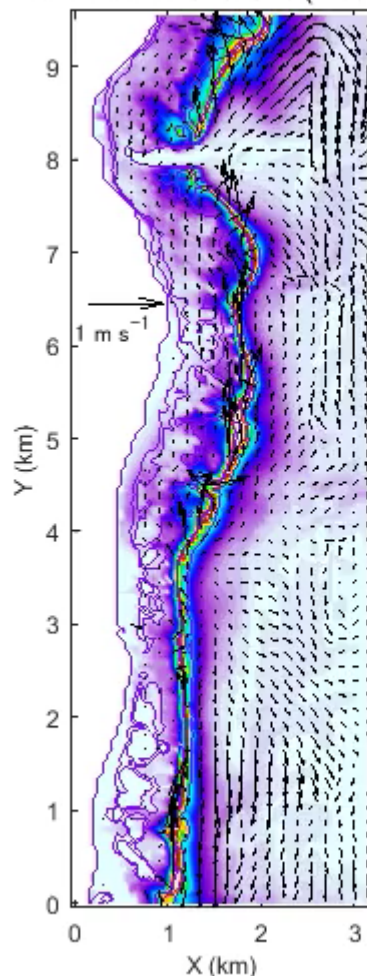
2023-10-08 00:00:00 (U

Significant wave height (m)



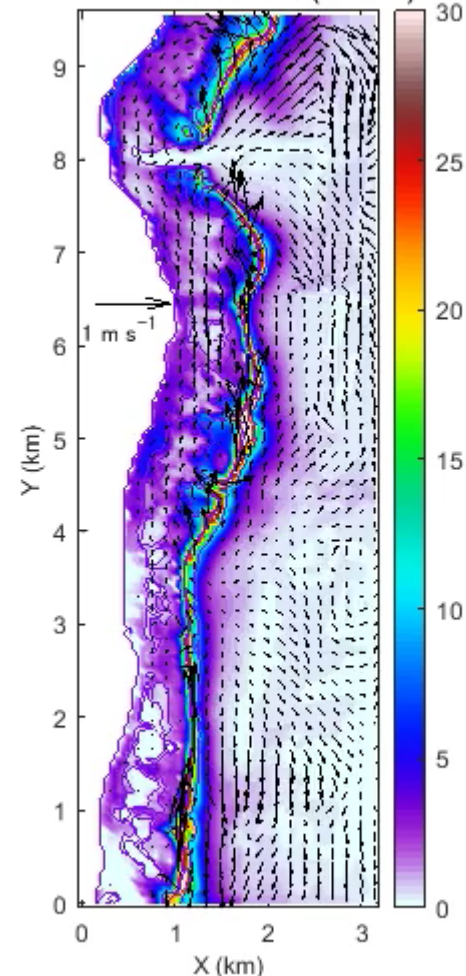
2023-10-08 00:00:00 (UTC)

Max bottom stress ($N m^{-2}$)



2023-10-08 00:00:00 (U

Max bottom stress ($N m^{-2}$)



2023-10-08 00:00:00 (UTC)

海草による赤土のトラップ効果

水柱底層の赤土濃度

海草有

Case 1

海草無

Case 2

計算期間中の

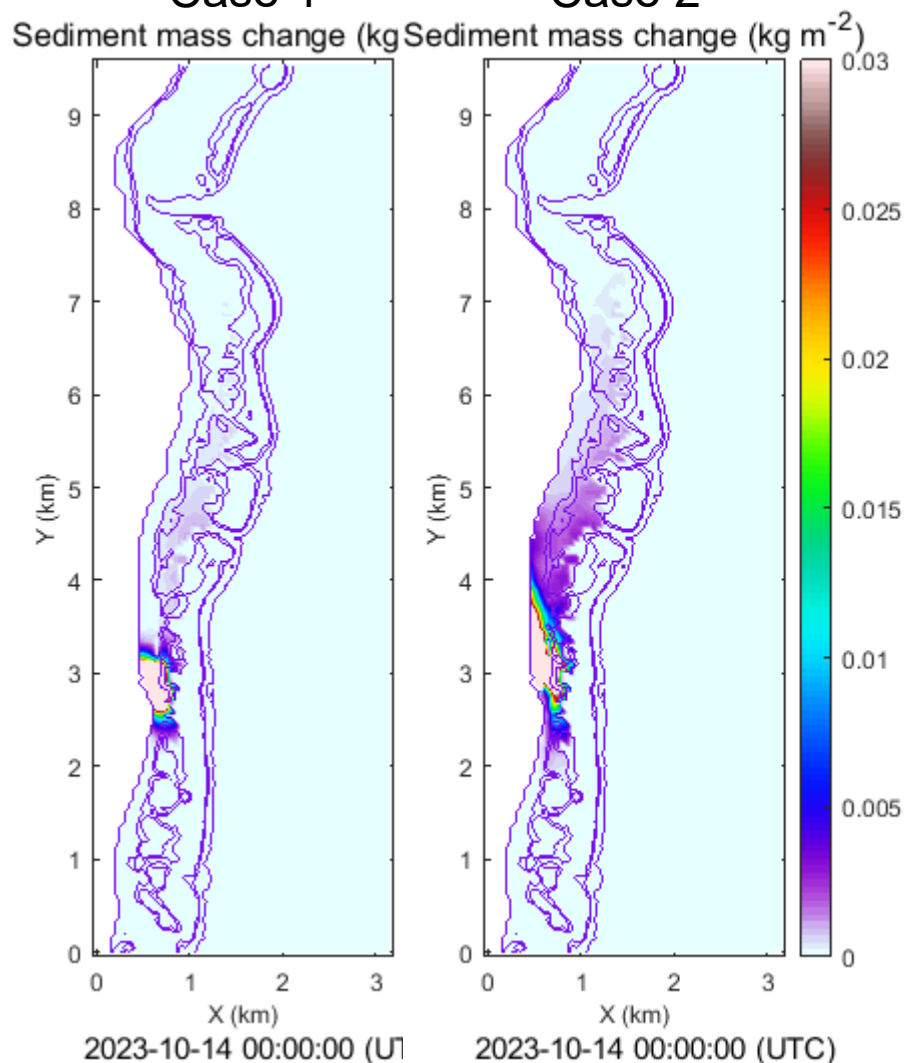
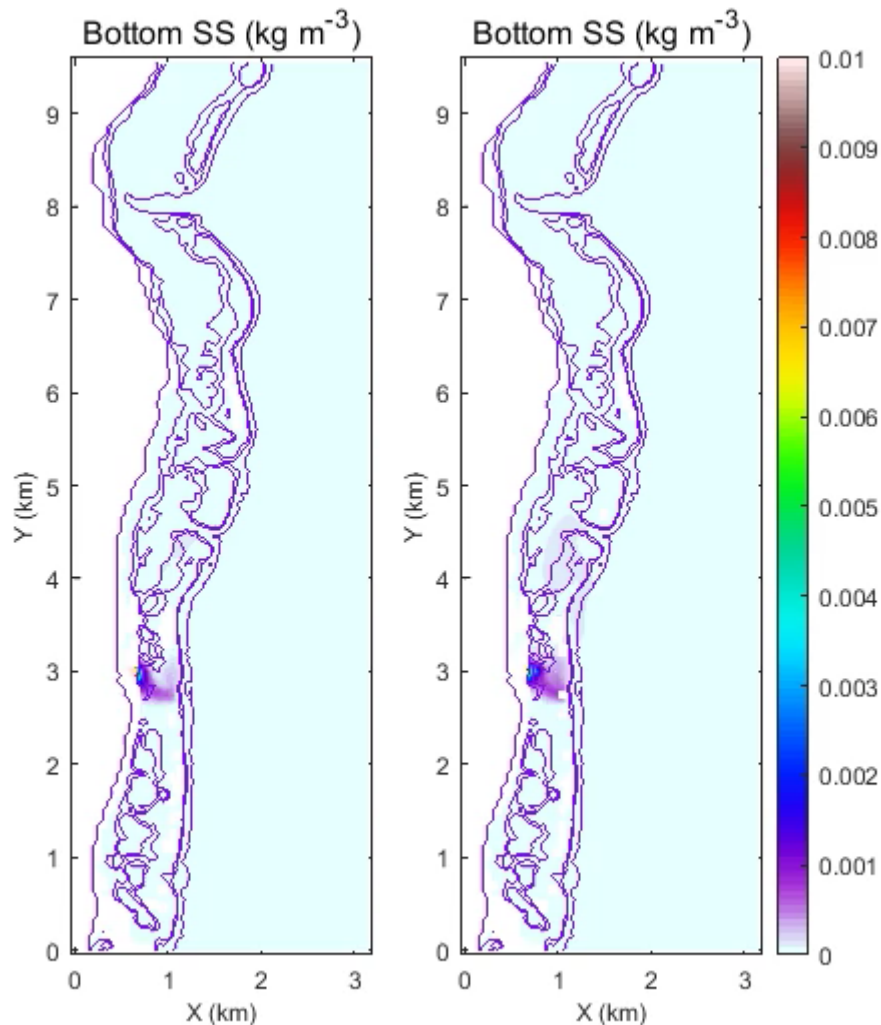
積算赤土堆積量

海草有

Case 1

海草無

Case 2



海草による再懸濁防止効果

水柱底層のSS濃度

海草有

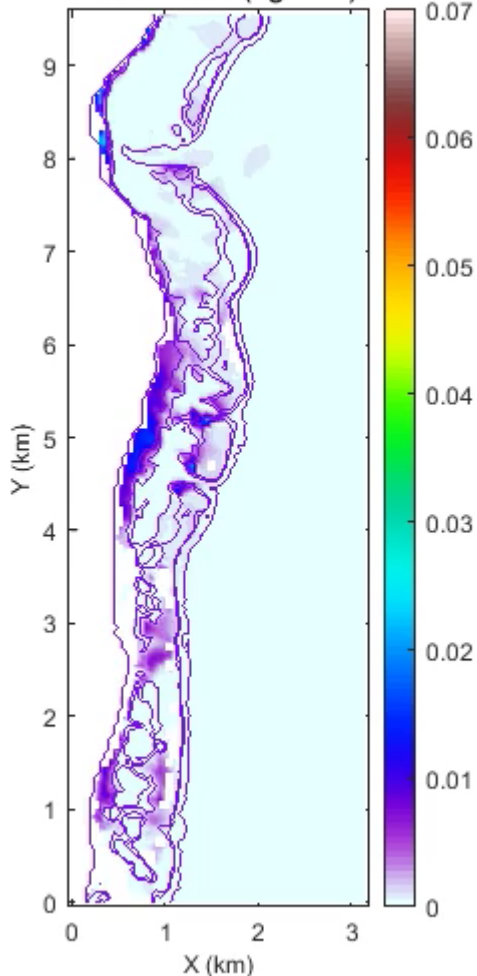
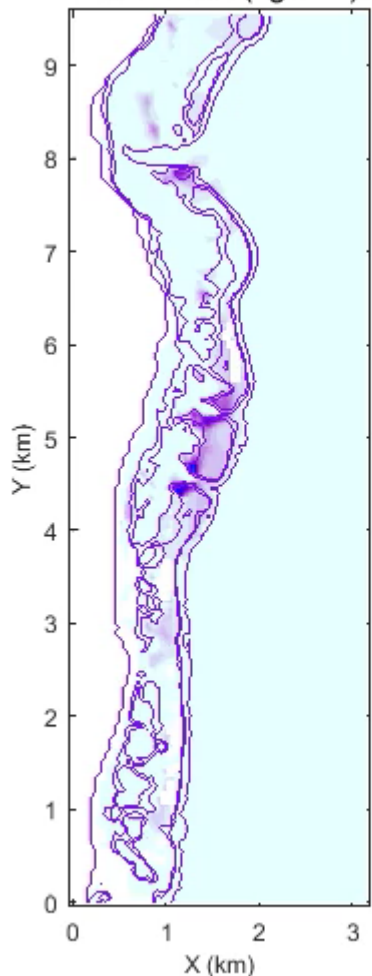
Case 1

海草無

Case 2

Bottom SS (kg m^{-3})

Bottom SS (kg m^{-3})



2023-10-08 00:00:00 (UTC)

2023-10-08 00:00:00 (UTC)

計算期間中のサンゴ礁堆積物の再堆積/浸食量

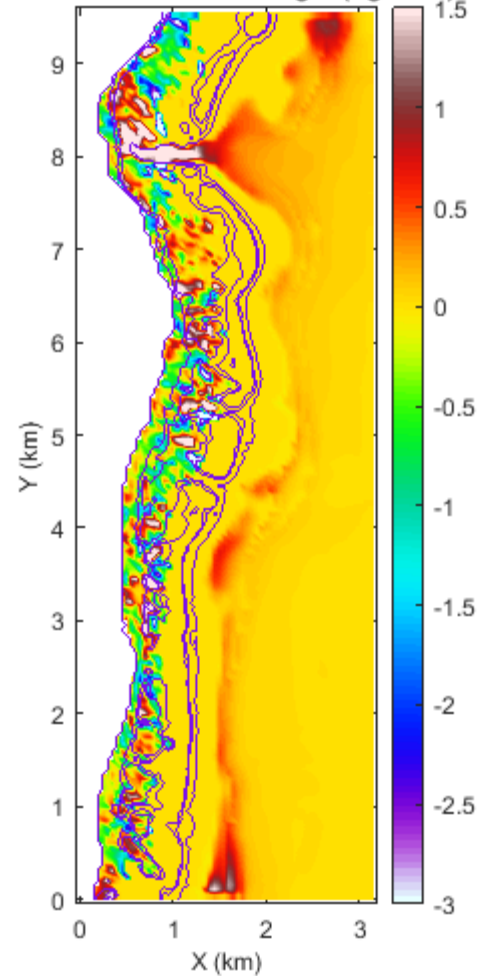
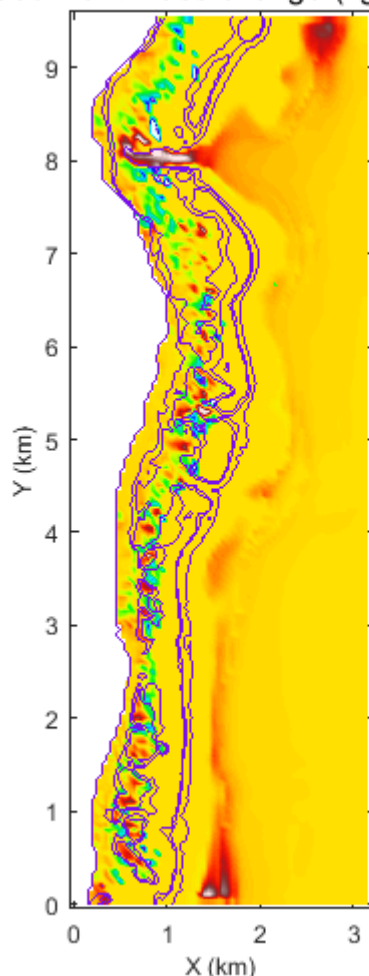
海草有

Case 1

海草無

Case 2

Sediment mass change ($\text{kg Sediment mass change (kg m}^{-2}$)



2023-10-14 00:00:00 (UTC)

2023-10-14 00:00:00 (UTC)

海草による陸源栄養塩負荷の緩衝機能

水柱底層の陸源DIN濃度

水柱底層の陸源PO₄濃度

海草有

海草無

海草有

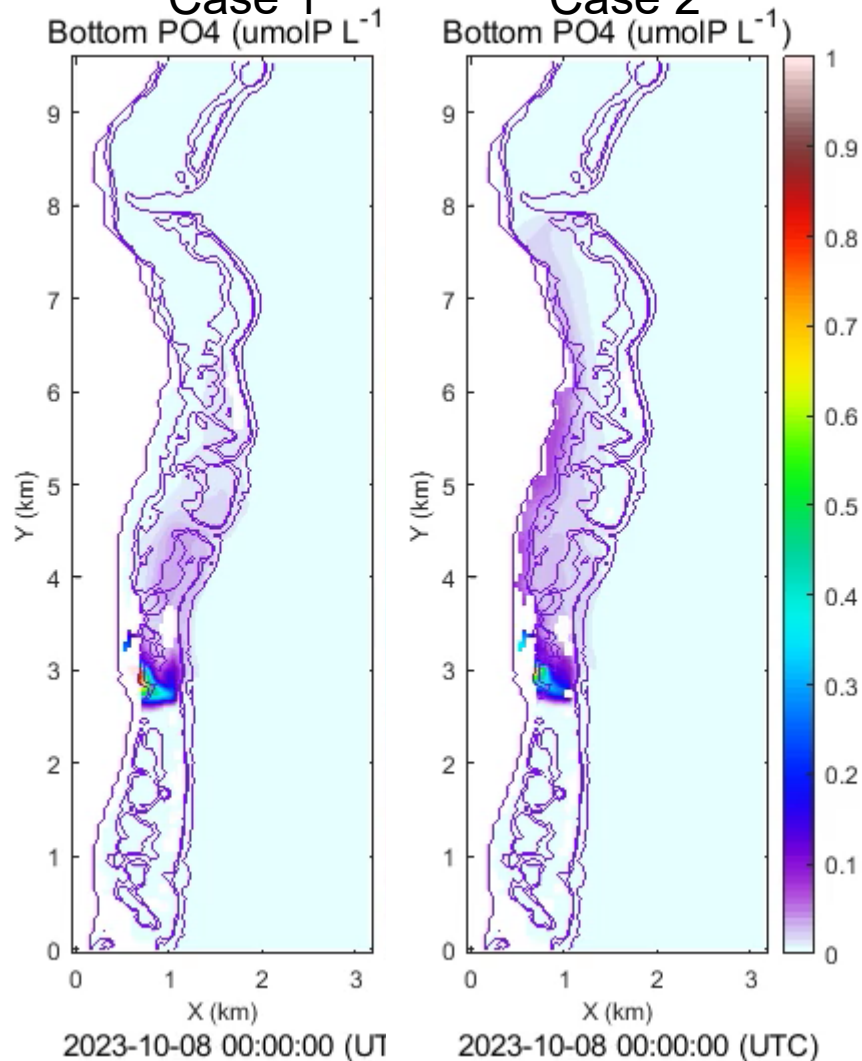
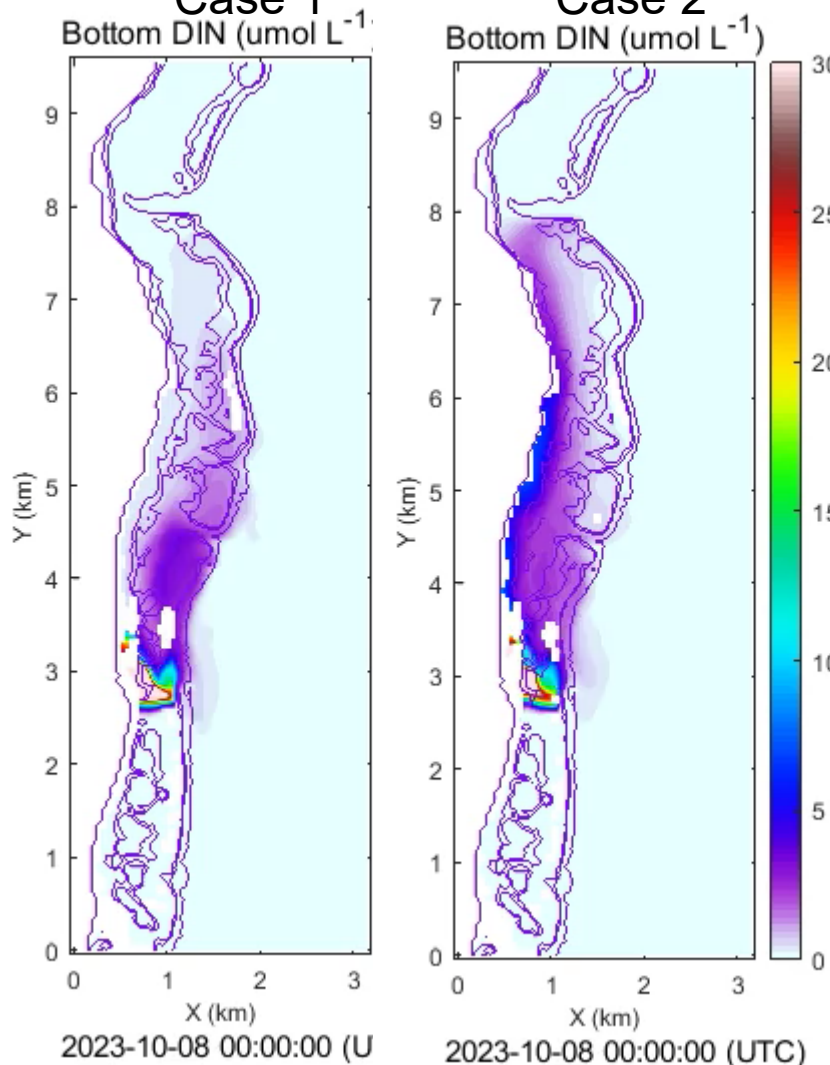
海草無

Case 1

Case 2

Case 1

Case 2



海草による陸源の栄養塩の緩衝機能

海草中のNバイオマス量

海草中のPバイオマス量

N全量

陸源のN量

P全量

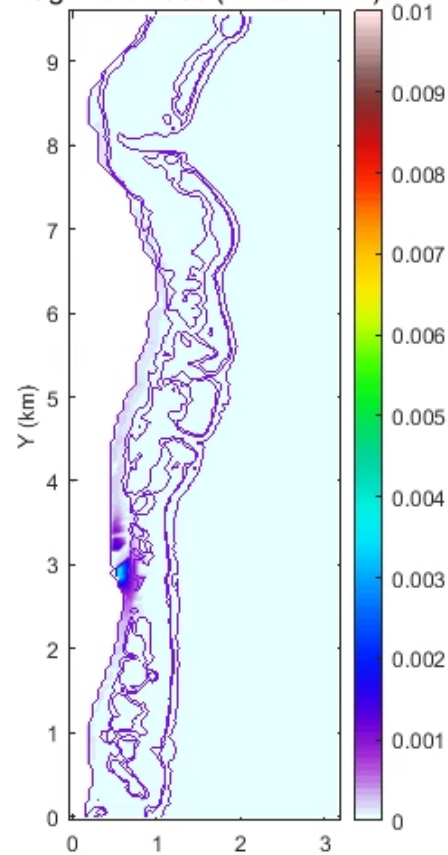
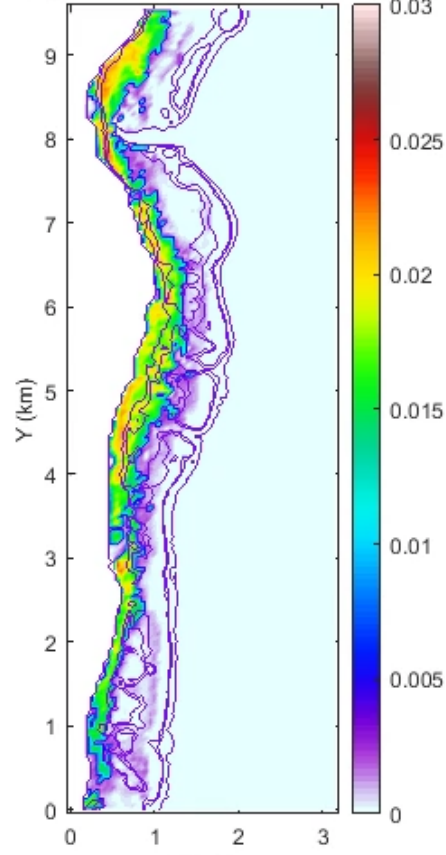
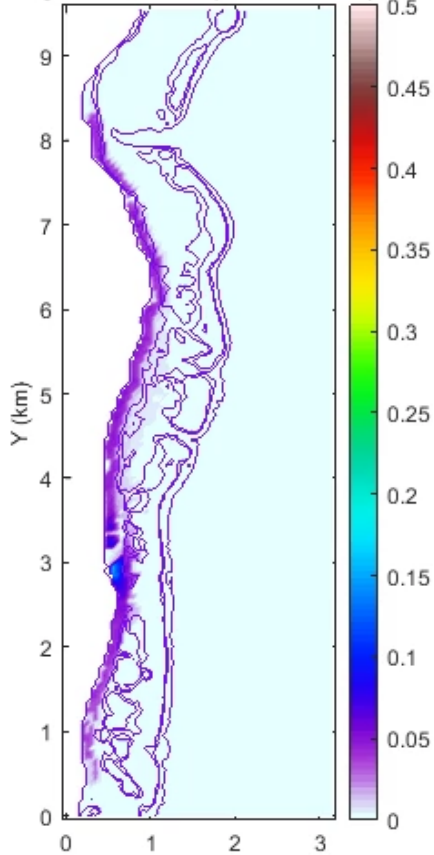
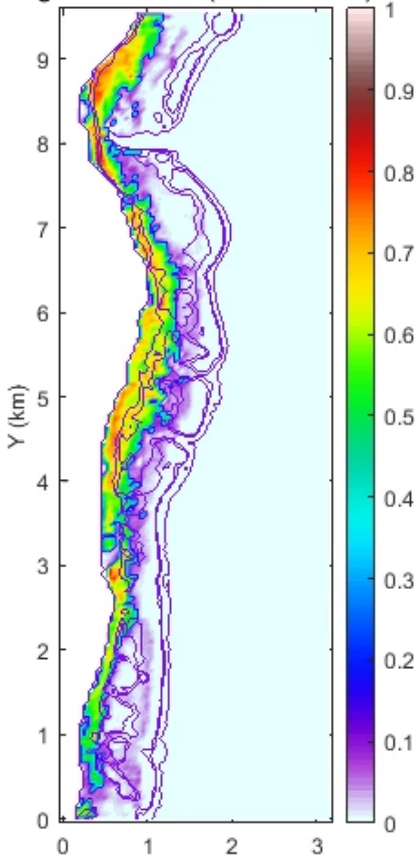
陸源のP量

Sg N biomass (mmolN m⁻²)

Sg N biomass (mmolN m⁻²)

Sg P biomass (mmolP m⁻²)

Sg P biomass (mmolP m⁻²)



2023-10-10 00:00:00 (UTC)

2023-10-10 00:00:00 (UTC)

2023-10-10 00:00:00 (UTC)

2023-10-10 00:00:00 (UTC)

Blue Carbon

ブルーカーボン: 海洋の生態系が生産した有機炭素。海草やマングローブ、塩生湿地などの生態系が主なブルーカーボンの生産者。主に海洋生態系のバイオマスとして、あるいは海底の堆積物中に貯留・隔離される。



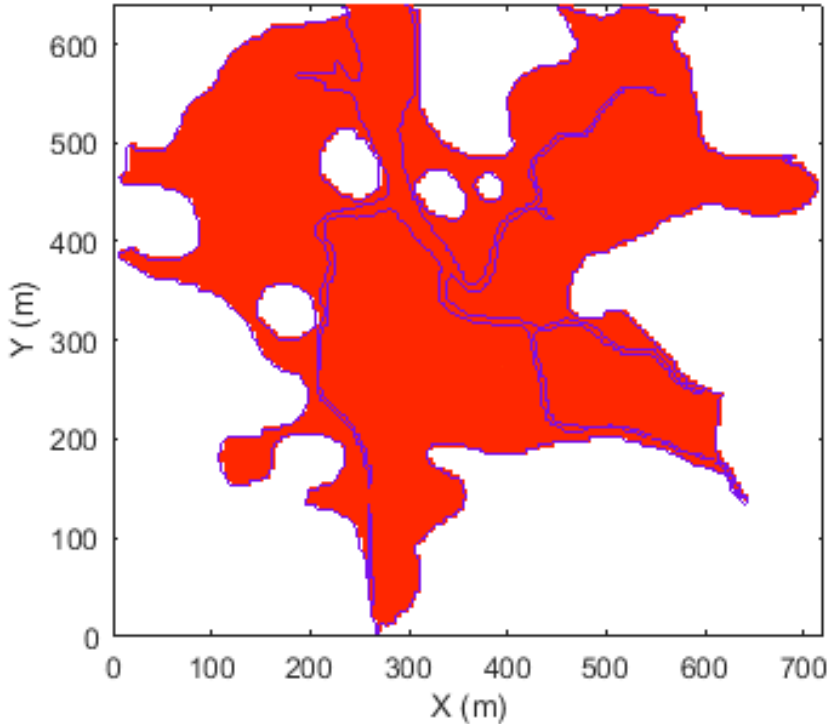
Figure 1.1 Blue carbon ecosystems: mangroves (top left, © Sterling Zumbrunn, CI), seagrasses (bottom left, © Miguel Angel Mateo), and tidal salt marshes (right, © Sarah Hoyt, CI)

(Howard et al., 2014)

Dynamic mangrove vegetation modeling

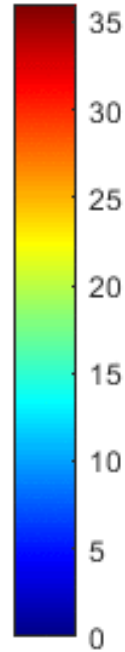


Salinity (psu)



2009-08-25 00:00:00(UTC)

Simulated spatio-temporal distribution of salinity by hydrodynamic model (ROMS)



Bird-eye view



Rhizophora stylosa
→ Salinity tolerant species.



Bruguiera gymnorhiza
→ Faster growth rate, salinity tolerance is weaker.

Major pathways of blue-carbon sequestration to the outer ocean

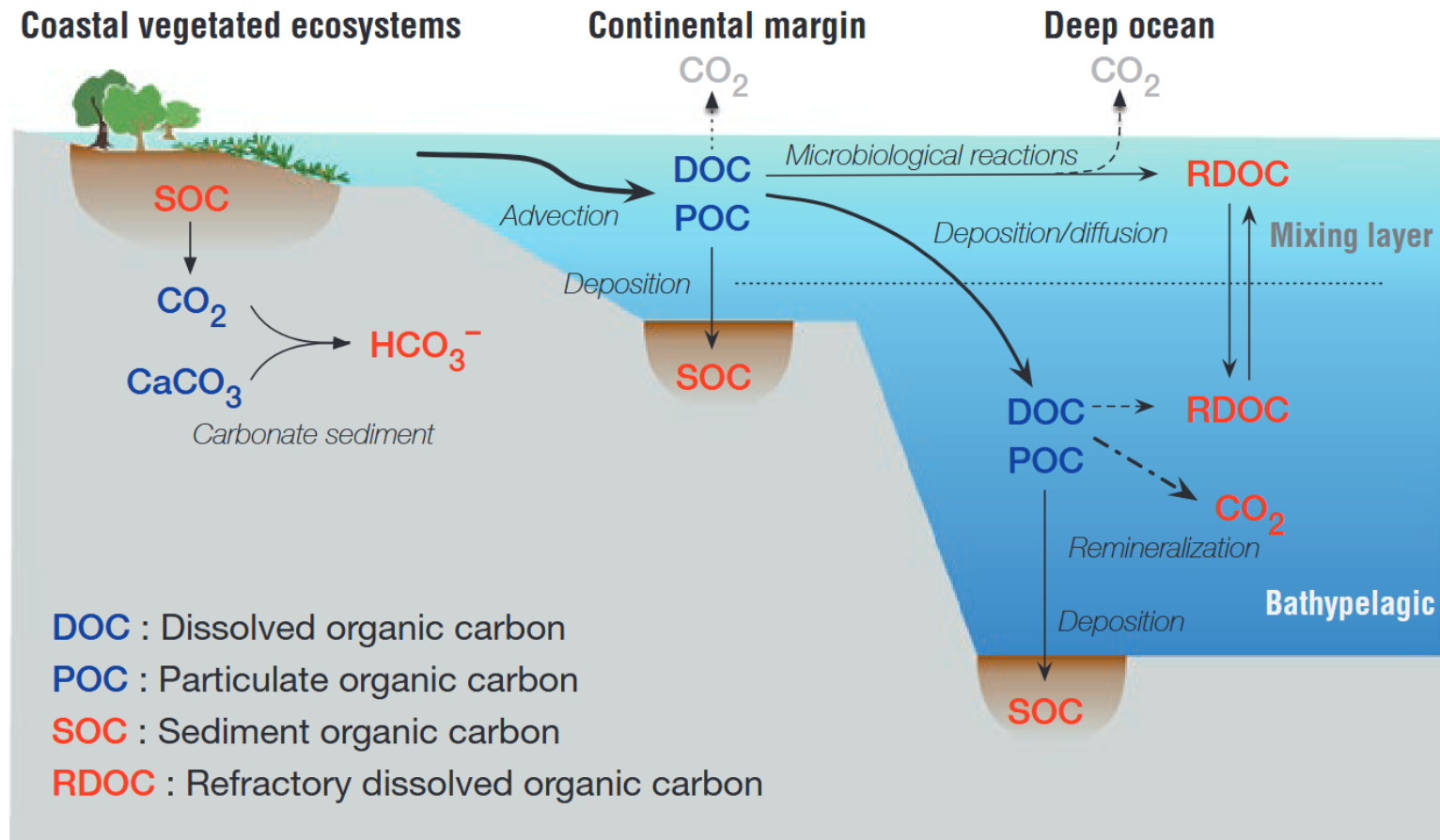


Fig. 2.8 Carbon export pathways from coastal vegetated ecosystems. OC produced in seagrass ecosystems may be potentially sequestered long term in the reservoirs marked by red letters, i.e., pelagic sediment OC (SOC), water-column bicarbonate (HCO₃⁻) and refractory dissolved OC (RDOC), and dissolved carbon dioxide (CO₂) in the bathypelagic water column

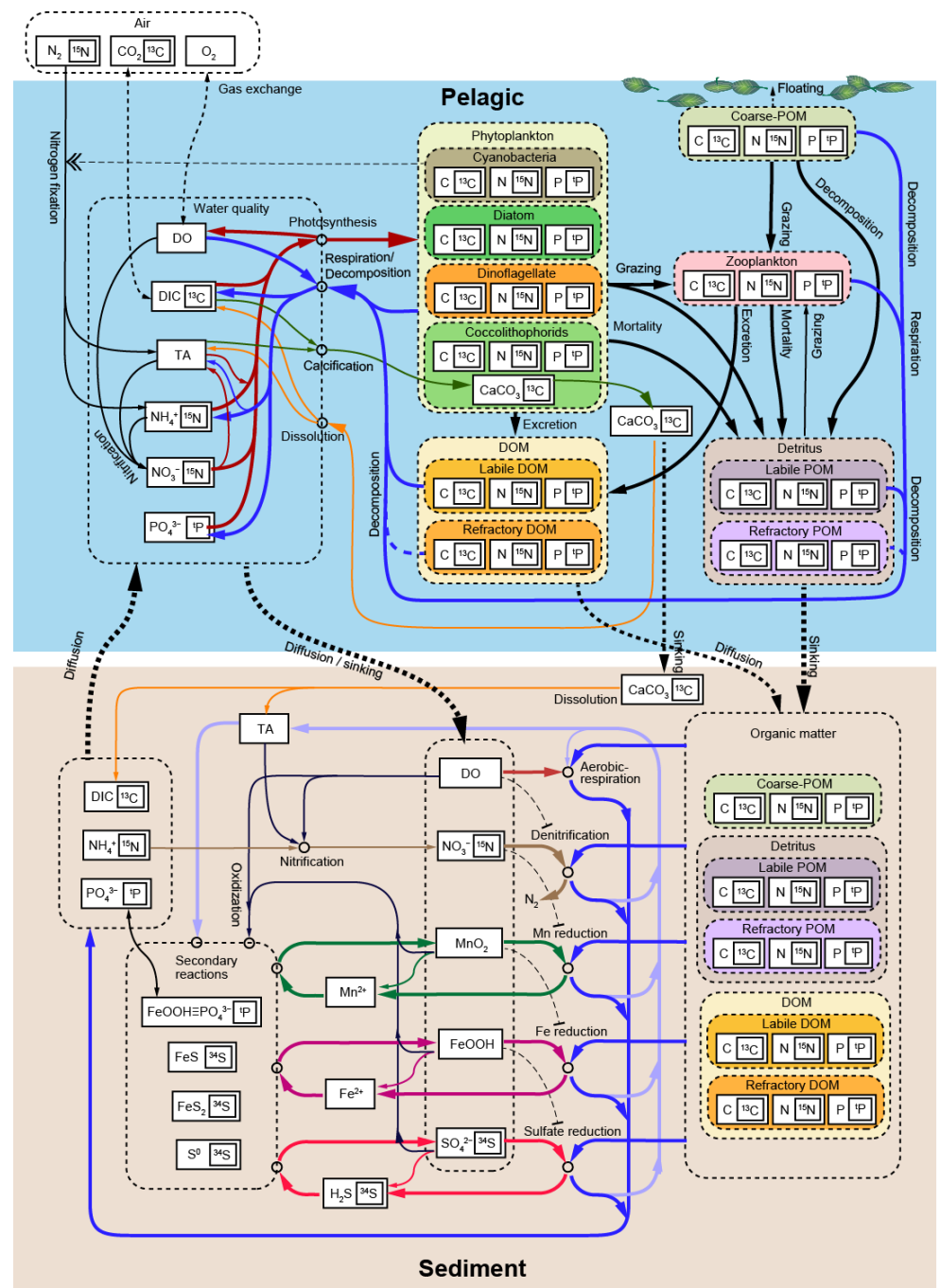
浮遊系-底生系モデル

A Marine Pelagic-Benthic Ecosystem Coupled Model with Element Tracers (Marine CoMET)

- 炭酸系パラメータの組み込み
- 4種類の植物プランクトン
- DOMとPOMの難分解性と易分解性のカテゴリ
- 粗大POM
- 堆積物中の詳細な酸化還元反応
- **C・N同位体/C・N・Pトレーサーの組み込み**
- 底生系ではS同位体/トレーサーも追加

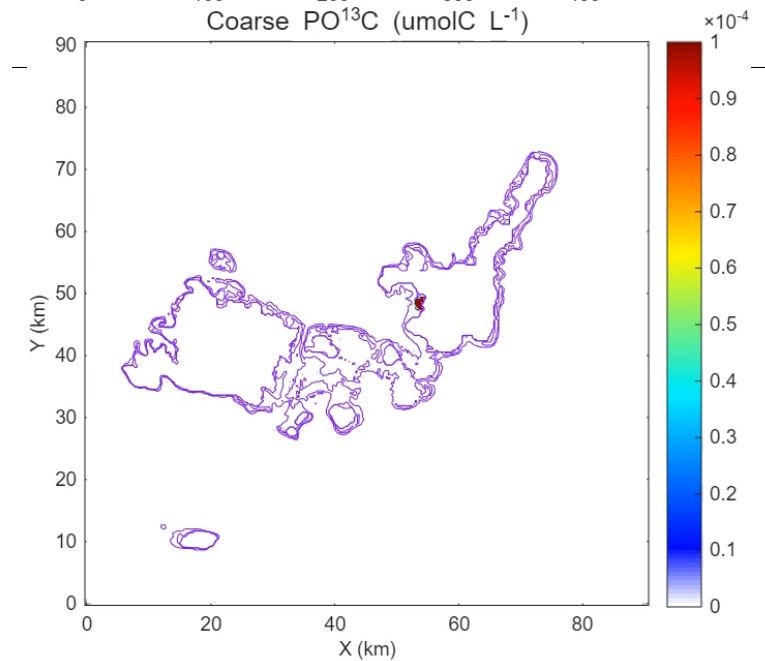
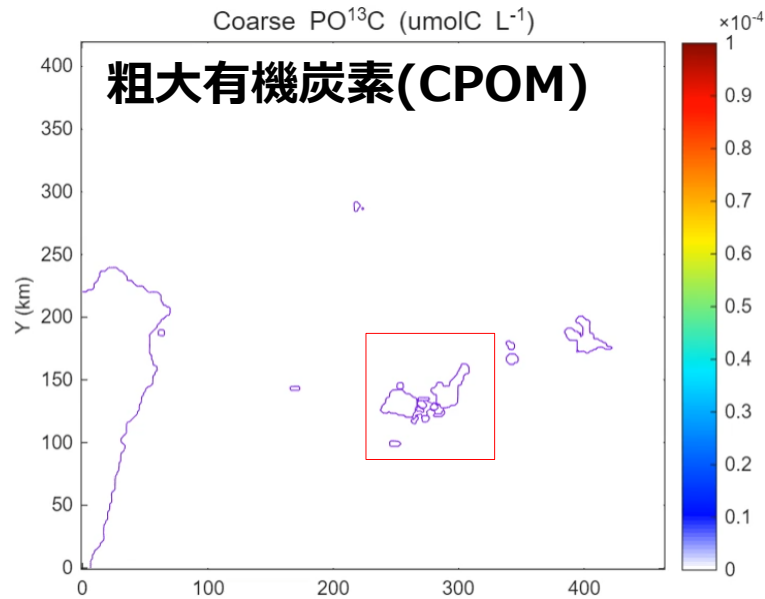


河川などの特定のソースからの炭素、窒素、リンの流転を追跡できるようになった！



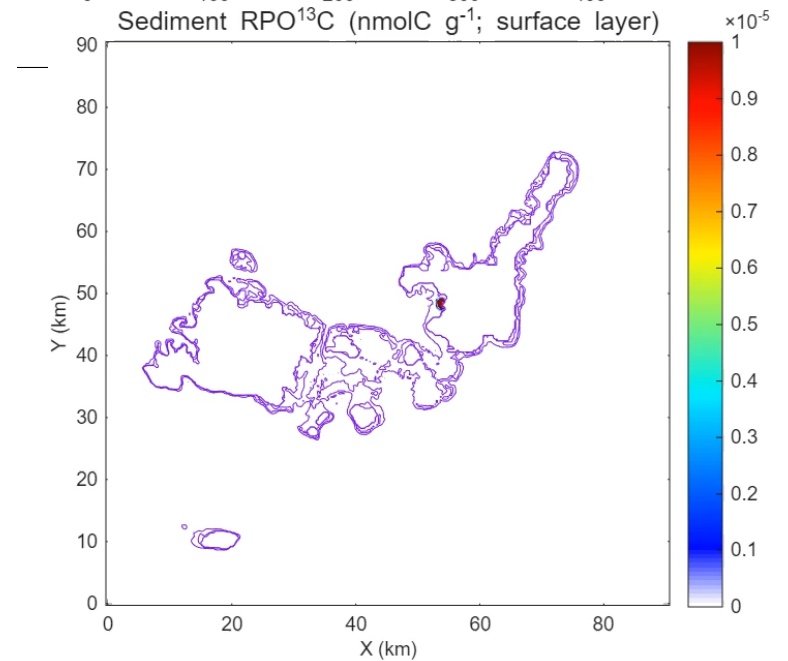
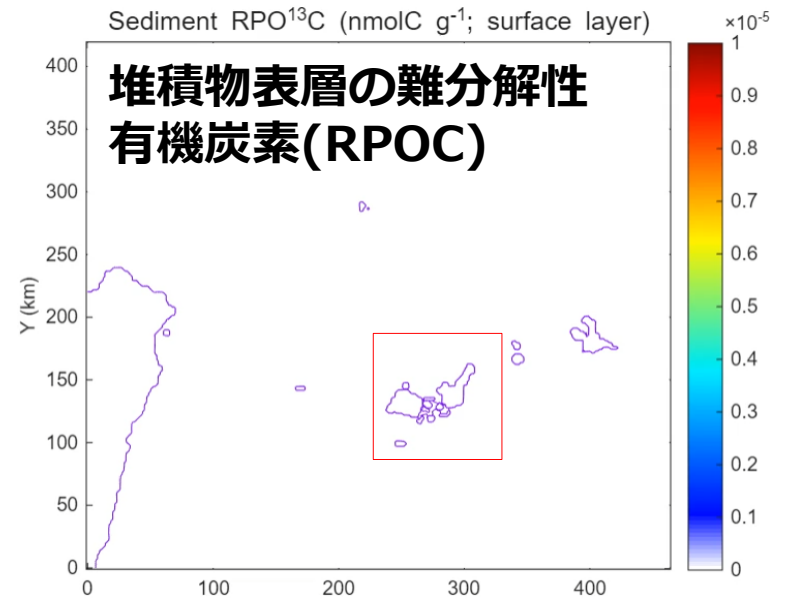
(Nakamura et al., in prep.)

マングローブの葉の分散経路



2019-08-01 01:00:00 (UTC)

マングローブの葉由来の有機物の堆積

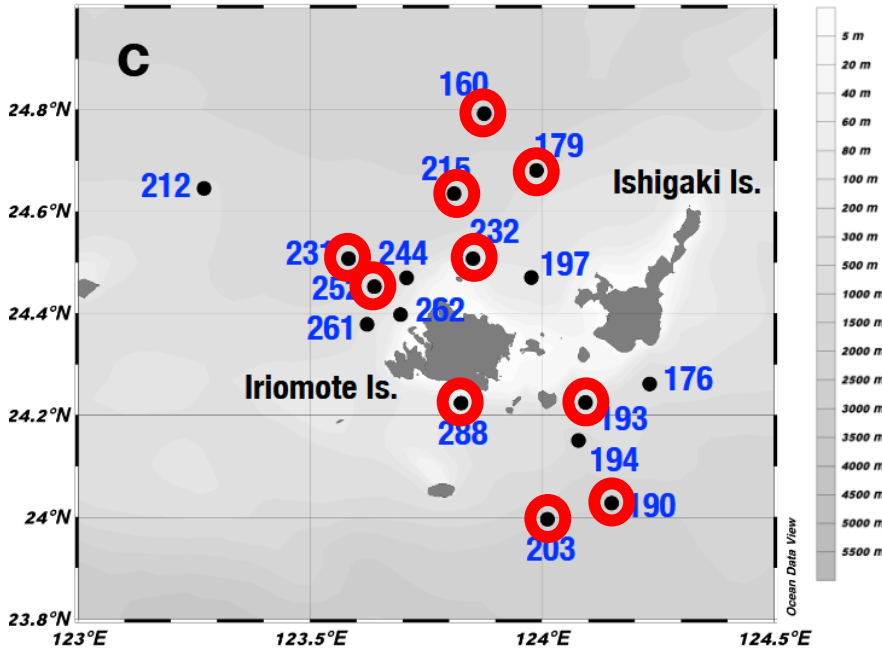


2019-08-01 01:00:00 (UTC)

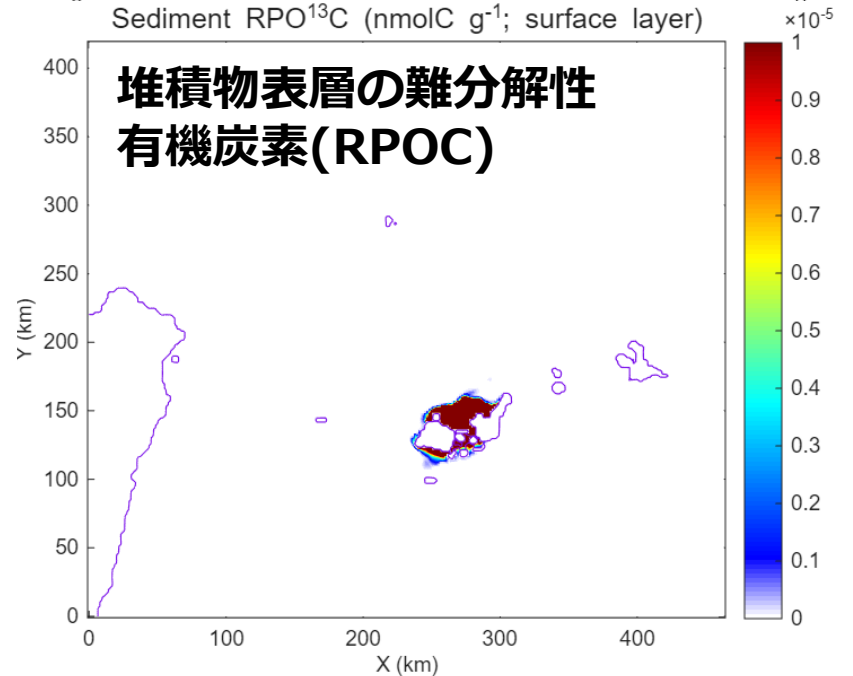
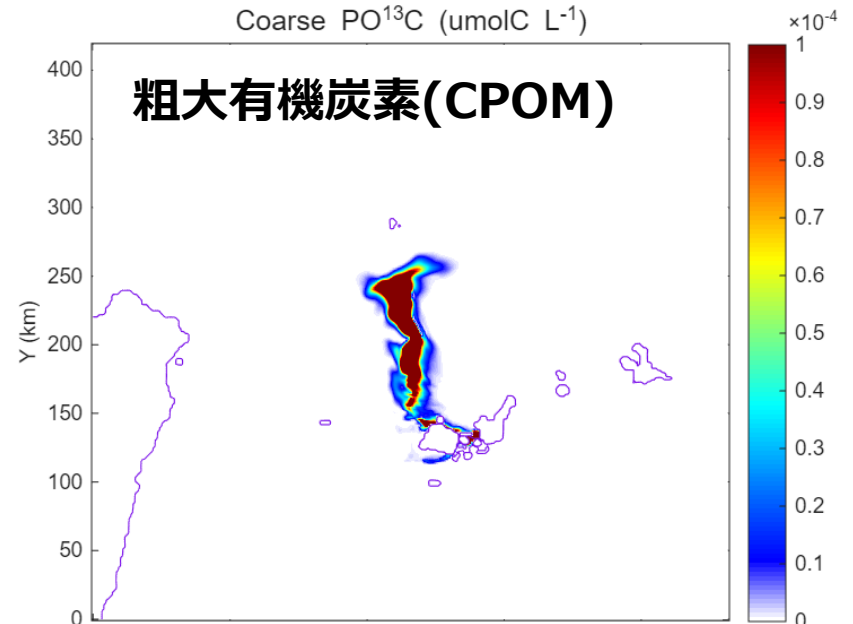
海底表層堆積物中でマングローブeDNAが検出された地点との比較

Table 1 Concentrations of DNA fragments detected in surface-sediment samples collected in coastal waters of the Yaeyama and Tokara areas (arranged from shallow to deep sites). Symbols: +++++, > 30,000; +++++, 10,000–30,000; +++, 3,000–10,000; ++, 890–3,000; +, 190–890; ±, 1–190; −, < 1 (unit: copies per gram dry weight of sediment). See text for a detailed description of the macroalgal categories. The tentatively defined detection and quantitation limits are 190 and 890 copies per gram (see text), respectively.

| Area | Site ID | Depth (m) | Mangroves | | | Seagrasses | | | | Macroalgae | | | | | | | | |
|--------------------------------------|---------|-----------|---------------------------|------------------------|-----------------------------|----------------------------|--------------------------|----------------------------|-----------------------|--------------------------------|------------------------------|------------|----------------------------|---|-------------------------|---|---|---|
| | | | <i>Rhizophora stylosa</i> | <i>Sonneratia alba</i> | <i>Bruguiera gymnorhiza</i> | <i>Thalassia hempralii</i> | <i>Enhalus acoroides</i> | <i>Cymodocea rotundata</i> | <i>Zostera marina</i> | <i>Sargassum</i> (subtropical) | <i>Sargassum</i> (temperate) | Ulva group | Cultivated <i>Porphyra</i> | Temperate kelps (<i>Ecklonia</i> , etc.) | <i>Saccharina</i> group | | | |
| Yaeyama coastal waters (cruise GK19) | 288 | 75 | ++++ | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . |
| | 262 | 110 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . |
| | 197 | 235 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . |
| | 232 | 253 | +++ | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . |
| | 193 | 327 | +++ | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . |
| | 261 | 444 | . | . | . | . | ++ | . | . | . | . | . | . | . | . | . | . | . |
| | 244 | 610 | . | . | . | . | . | . | ++ | . | . | . | . | . | . | . | . | . |
| | 176 | 676 | . | . | . | . | ++ | . | . | . | . | . | . | . | . | . | . | . |
| | 212 | 832 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . |
| | 252 | 952 | +++ | . | . | . | +++ | . | . | . | . | . | . | . | . | . | . | . |
| | 194 | 987 | . | . | . | . | . | . | +++ | . | . | . | . | . | . | . | . | . |
| | 231 | 1242 | ++++ | . | . | . | ++ | . | . | . | . | . | . | . | . | . | . | . |
| | 215 | 1665 | ++++ | . | . | . | ++ | +++ | . | . | . | . | . | . | . | . | . | . |
| | 179 | 1759 | ++++ | . | ++++ | . | ++ | +++ | . | . | . | . | . | . | . | . | . | . |
| | 203 | 1839 | ++++ | . | . | . | ++ | +++ | . | . | . | . | . | . | . | . | . | . |
| | 160 | 1887 | ++++ | . | +++ | . | ++ | +++ | . | . | . | . | . | . | . | . | . | . |
| | 190 | 1985 | ++++ | ± | +++ | . | . | . | . | ± | +++ | . | . | . | . | . | . | . |



○ マングローブのeDNAが検出された地点
(Miyajima et al., 2022)



An underwater photograph of a coral reef. The foreground is dominated by a dense field of branching, yellowish-green corals. The background shows a vast expanse of the reef extending into the distance under a clear, blue sky. The lighting is bright and even, highlighting the intricate textures of the coral.

ご静聴ありがとうございました