Introduction to the Connectivity of Hills, Humans and Oceans (CoHHO*): Figure out how they interact with each other

*We call it "Mori - Sato - Umi Renkan - Gaku" in Japanese.

(2) "Nutrients" that nurture living creatures in the sea

Emeritus Prof. Yoh Yamashita

In the first article of the Introduction to the CoHHO, I introduced the principal idea and the beginning of the CoHHO. Now, I would like to take a look at the CoHHO from the point of the sea.

In an ecosystem from forests to the sea, various substances (including all sorts of substances such as: chemical substances in water, soil, rubbish, and living creatures) get carried from land to the sea through rivers and groundwater. Such movement or transportation of substances is called 'the biogeochemical cycle'. In case of living creatures such as salmon that migrate from the sea to rivers at the end of their lives, substances move from the sea to rivers and/or land. Furthermore, if sea water evaporates and falls as rain after being transported to land, then this becomes movement of substances from the sea to land. However, in most cases, the sea is positioned at the downstream end of the biogeochemical cycle. Therefore, I would like to consider the connectivity and fragmentation between forests, rivers, *Sato* (areas where people live) and the sea in terms of substances that are transported from land to the sea.

Substances that are transported from land to the sea include the following: 1. water (river water), 2. nutrients (nutrient salts), 3. organic matter, 4. inorganic particles, and 5. toxic substances (e.g. pesticides). In addition, 3. organic matter also includes 6. animals. However, 6. animals will be considered separately here, since they are able to move independently compared to 3. organic matter, which refers to dead animals/plants or their decomposed substances. Here, I will consider how human activities affect these substances and living creatures, and how this affect the environment and ecosystems. I will begin by focusing on nutrients that support growth and proliferation of coastal life, and on river water that transports them from land to the sea.

1. Importance of estuaries and coastal areas

To begin with, I will consider the function of estuaries and coastal areas, located in the most downstream part in the flow of forests, rivers, *Sato*, and the sea. Estuaries and coastal areas are enriched with nutrients and these areas are extremely productive biologically. Thus, many aquatic animals use these areas as their dwelling, spawning, and nursery grounds during their juvenile stage. Moreover, healthy conditions are required in estuaries, since estuaries play a key role in diadromous migration (i.e. migration between riverine and marine environments in the life history). Many diadromous fish species are important in fisheries, such as salmon (*Oncorhynchus keta*), Japanese eel (*Anguilla japonica*), temperate seabass (*Lateolabrax japonicus*), and Ayu sweetfish (*Plecoglossus altivelis*). Additionally, estuaries are enriched with tidal flats and seaweed/seagrass beds, which give these areas high capacity to purify water and mud on the seafloor. Such environmental purification and other blessings of nature, including food production, are called ecological services. Costanza et al. (1997) were the first to estimate the economic value of ecological services by converting them to money. In this paper, they found that coastal seaweed/seagrass beds, estuaries, and tidal flats are considered the most valuable ecosystems for mankind (Fig. 1). However, since Japan prioritized economic development long after the post war recovery period, we have lost a lot of the shallow waters in the sea due to reclamation and revetment. Even thinking simply, we can say that the environmental purification capacity and the productivity of aquatic animals (fish and invertebrates including shellfish, shrimp, crab, octopus and squid) in the area of reclaimed shallow waters have been lost. Moreover, vertical concrete revetment in many reclaimed lands has a negative impact on the surrounding aquatic environments and can cause red tide and hypoxia. Hypoxic areas in coastal waters are called 'dead zones', because living creatures cannot inhabit them. Even now 'dead zones' continue to spread globally. Reclamation is not the only cause of deterioration in estuaries and coastal areas, which play vital roles in environmental conservation and biological production. Human activities on land also have a great impact on the environment and ecosystems of coastal areas. Our research group used a technique called environmental DNA metabarcoding and scientifically demonstrated that concrete revetment of estuaries and coastal areas pose a negative impact on the survival of endangered species (Kume et al. 2021).

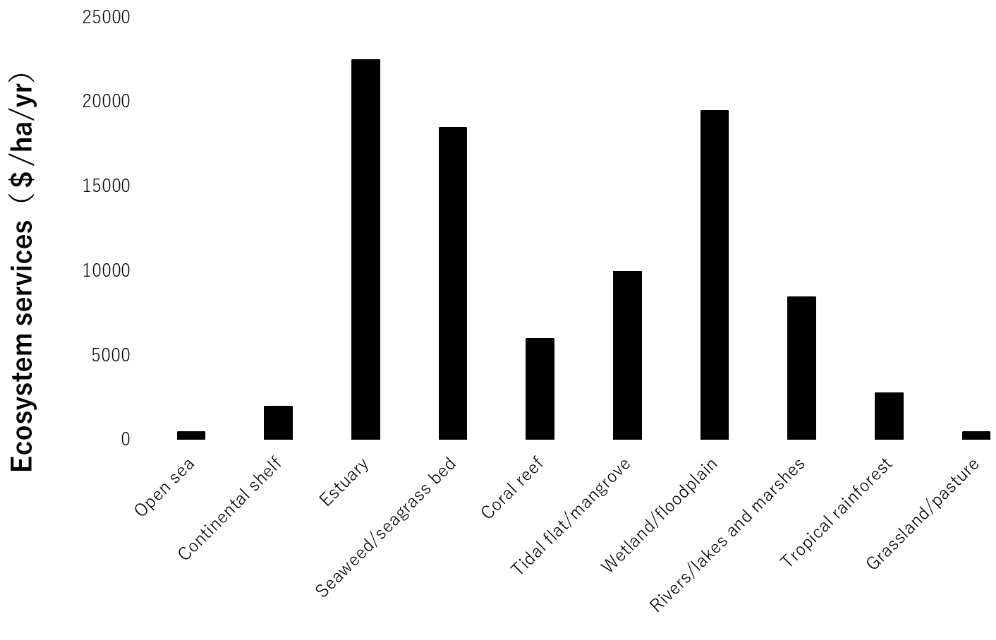

Figure 1. Value of ecosystem services. Adapted from Kasai (2014) using the data of Constanza et al. (1997).

2. The role of river water flowing into the sea

In the research field of land water use, some say that efflux of precious freshwater into the sea is a waste of resources, and we should maximize its usage by storing it in dams and reservoirs. However, this is an obvious mistake when we view it from the point of the marine ecosystems. Influx of rich river water into the sea is a lifeline for the environment and ecosystems of estuaries and coastal areas. Examples of drastic deterioration in the environment and ecosystems of the hydrosphere (the sea) through a decline in river discharge can be seen in Nile River (Mediterranean Sea) and Aral Sea.

In modern society, water is an indispensable natural resource for human lives and economic activities. River water stored in dam lakes and reservoirs is managed and exploited for water utilization (power generation, agricultural and industrial water, drinking water, etc.) and flood control (prevention of floods). Thus, the amount of river water reaching the sea is significantly reduced. In addition, discharge becomes seasonally less distinctive, and it tends to be levelled out to a low standard. Then, what happens when river discharge declines? There used to be clear seasonal changes in river water influx before the rapid economic growth period after the war. It is conceivable that living creatures in estuaries and coastal areas have survived by developing life histories adapted to natural seasonal changes over a long period of time. However, various problems arise when river discharge declines. For example, in Seto Inland Sea where winter rainfall is low, nutrient deficiency is thought to prevent algae from growing. Additionally, a decline in discharge may also prevent juvenile Ayu sweetfish from migrating upstream from the sea. It is also reported that the levelling out of discharge is an advantageous condition for dinoflagellates that cause harmful red tides (Yamamoto 2007).

River discharge also significantly affects the physical environment of estuaries and coastal areas. Due to its lower density compared to sea water, river water flows out offshore in the surface layer after entering the sea. This surface flow in the offshore direction becomes a driving force to make the bottom flow in the onshore direction. Thus, a circulatory flow occurs offshore of the estuary with the surface layer moving offshore, and the lower layer moving onshore. This is called estuarine circulation (Fig. 2) and plays a vital role in supplying nutrient salts that support the proliferation and growth of aquatic plants (e.g. phytoplankton and seaweed). As for nutrient salts, I will discuss later in detail. Estuarine circulation is also important for the supply of oxygen. Oxygen is indispensable for living creatures in water. After oxygen from air dissolves in surface water, it is carried to the bottom by vertical mixing (up and down movement) of sea water. Therefore, when estuarine circulation weakens with a decline in river discharge, oxygen does not get carried down and it can create hypoxic water masses in the bottom layer.

Toyokawa River runs into an already hypoxic Mikawa Bay, but a new dam (Shitara Dam)is under construction. Reducing the discharge on Toyo River could further destroy the environment of Mikawa Bay. The committee on marine environmental issues of the Oceanographic Society of Japan (2008) released a statement on its periodical publication

(Oceanography in Japan) opposing the dam construction. There are also strong ongoing oppositions from the locals.

Rain that falls on land is released into the atmosphere via evaporation and transpiration of plants. Forests are called ‘green dams’, and according to Unoki (2015), the ratio of evapotranspiration to precipitation is: 54% in forests, 68% in grasslands, and 66% in arable lands. The infiltration capacity (mm/h) of water into the surface soil is: 272 in deciduous forests, 211 in coniferous forests, 143 in natural grasslands, 107 in artificial grasslands, 89 in fields, and 13 in pedestrian roads. This reveals the high water retention capacity of forests. Forests moderate the effect of heavy rainfall and drought though their water retention capacity. This function of forests helps to maintain river discharge and prevent extreme changes such as floods.

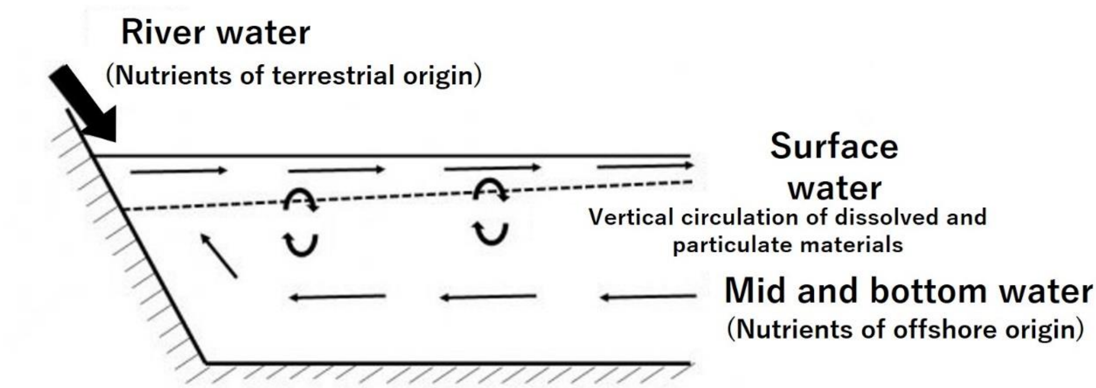

Figure 2. Estuarine circulation

3. Do rich nutrients of forests nurture the sea?

You may have heard of the expression “Rich nutrients of forests nurture the sea.”. Primary production, which supports biological production in the hydrosphere, begins with photosynthesis of aquatic plants, such as phytoplankton, benthic microalgae, seaweed and seagrass. Since aquatic plants absorb elements required for proliferation and growth in the form of salts, they are called nutrient salts. High productivity of estuaries and coastal areas are supported not only by nutrient salts from land, but also by nutrient salts supplied from offshore bottom water through estuarine circulation. In other words, a decline in river discharge will not only reduce the nutrient salts suppled from land, but also weaken the driving force of estuarine circulation and decrease the amount of nutrient salts supplied from offshore. In our research field of Tango Bay in Kyoto Prefecture, we have revealed that nutrient salts supplied from offshore bottom water though estuarine circulation is more important for primary production compared to nutrient salts supplied from land (Watanabe et al. 2017).

Important elements of nutrient salts are nitrogen, phosphorus, and silicon. Especially diatoms, a representative group of phytoplankton and an important food source for aquatic animals, require silicon for cell walls and consume a lot of it. To judge which element is most scarce in water, the molar ratio of elements in diatom cells is used as a standard scale. This ratio is called the Redfield ratio, and the molar ratio of nitrogen:phosphorus:silicon is 16:1:15 (or 16). On the other hand, dinoflagellates that include many species of toxic plankton and cause harmful red tides do not need much silicon. Therefore, the balance of elements is just as important as their concentrations. If nutrient salts including silicon are well balanced, diatoms outcompete and dominate, as they have higher growth rate compared to dinoflagellates. Since diatoms contribute to primary production, the dominance of diatoms in the sea is generally regarded as a healthy environmental condition. However, silicon is mainly supplied by the soil, whereas phosphorus and nitrogen are released both from natural sources and human activities. Therefore, when diatoms consume nutrients according to the Redfield ratio, silicon concentration becomes comparatively low in coastal waters. The nutrient imbalance triggers severe outbreaks of toxic phytoplankton such as dinoflagellates (red tide) to seriously damage aquaculture farms.

Liebig's law of the minimum is a concept used to identify what factor is most limiting in the photosynthesis of aquatic plants. This concept is illustrated in the Liebig's barrel, which includes factors, such as temperature and light in addition to nutrient salts (Fig. 3). This diagram demonstrates how the shortest stave (factor) determines the capacity of the barrel, i.e. the rate of photosynthesis (productivity). The occurrence of dinoflagellate red tides mentioned above can be explained by silicon deficiency as a limiting factor. When silicon is deficient, diatoms cannot grow even under nitrogen and phosphate rich condition. Instead, dinoflagellates that hardly require silicon proliferate, consuming the surplus of nitrogen and phosphate.

Then, what about the supply of nutrient salts from forests to rivers? Nitrogen utilized in forests originates from the atmosphere. It is taken into forest ecosystems via nitrogen compounds in raindrops and nitrogen fixation by legumes and soil microorganisms. By nature, forest ecosystems have a recycling mechanism to keep as much nitrogen as possible within, since nitrogen is often deficient in the production of plants on land. In other words, forests have a way to keep nutritional substance within the system, including phosphorus. Even in the Yura River basin, our main research field, nitrogen and phosphorus supplied from forests were minimal, and most were discharged from farmlands and cities. We found that rich forests do not necessarily supply rich nutrients to rivers and the sea in the Yura River basin (Fukusaki et al. 2014).

On the other hand, nitrogen compounds are increasing in the atmosphere in recent years due to combustion of fossil fuels (homes, factories, and exhaust fumes from vehicles). They in turn fall on forests, and excessive nitrogen is reported in forests that were originally considered to be deficient in nitrogen. This phenomenon is called nitrogen saturation (Fig. 4). In our investigation in Kunisaki Peninsula of Oita Prefecture, we confirmed that nitrogen concentration is its highest around the peak of Mt.Futago in the middle of the peninsula. This abundant nitrogen then dissolves in stream waters and decreases downstream as river creatures utilize it. Out of the dissolved nitrogen of high concentration, less than 4% entered the streams directly. Most of it was taken up and used by forest ecosystems and the rest was pushed out into rivers as excess. More interestingly, biological production tended to be higher in rivers that run through nitrogen - saturated forests in Kunisaki Peninsula than in neighboring rivers that have low concentrations of dissolved nitrogen (normal rivers in some sense). How we interpret this within the idea of CoHHO is a complicated issue. If forests are saturated with nitrogen by large amounts of nitrogen compounds supplied from the atmosphere, it can have negative impacts. For example, risks of landslides and other hazards could occur if forest vegetation on forest soils (forest floors) are damaged as a result of soil acidification. Stream water can also be acidified, which will make it inhabitable for living creatures. Looking at it from a different angle, if nutrient nitrogen is supplied from forests to the hydrosphere within a range that will not negatively impact the environment, then we can expect an increase in productivity in rivers and the sea. We will need further accumulation of scientific knowledge and careful discussion to consider the issue of nitrogen saturation and nutrient salts supplied from forests to the hydrosphere.

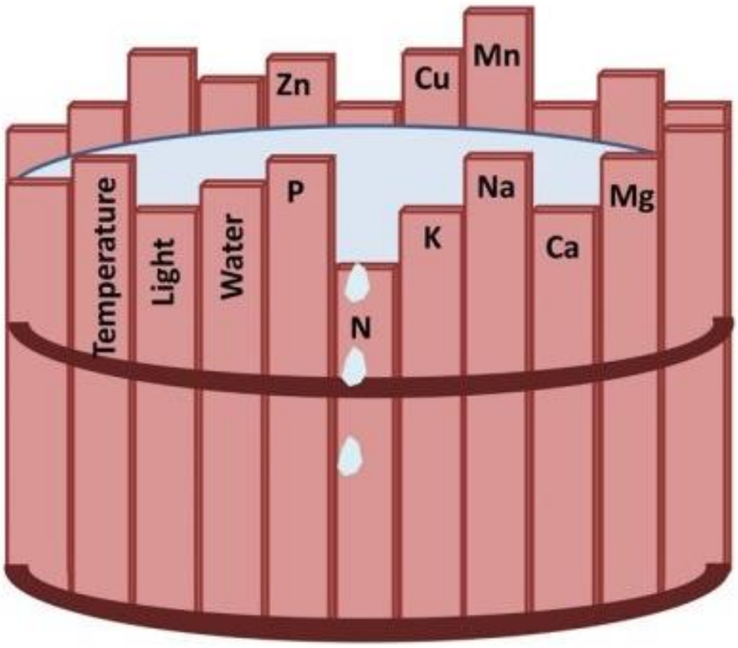

Figure 3. Liebig's barrel. In this example, nitrogen (N) with the shortest stave determines the capacity (primary productivity) of the barrel (Tateno 2014).

Below is the interpretation from our research team in Kunisaki Peninsula to supplement the paragraph above (Sugimoto et al. 2021). In Kunisaki Peninsula, nitrogen is in excess upstream with N/P ratio of above 50, since large amounts of nitrogen is supplied from forests. However, nitrogen is reduced through denitrification and bio - utilization in reservoirs and paddy fields, which are traditional agricultural and irrigation systems of Kunisaki Peninsula. Furthermore, phosphorus is supplied through fertilizers, sediment particles, and human activities from farmlands/paddy fields and residential areas. Therefore, in the coastal areas of the two main rivers of Kunisaki Peninsula, Aki River and Katsura River, nutrient salts with a ratio close to the Redfield ratio were being supplied to the sea. Our co - researchers Yokoyama et al. (2019a, b) reported that batillariid snail (*Batillaria* *multiformis*), an important secondary producer in estuaries, feeds mainly on microalgae that were produced with nutrient salts of terrestrial origin. Moreover, in the coastal areas of Oita Prefecture, temperate seabass juveniles migrate from the offshore spawning ground into estuaries and use them as nursery grounds during the irrigation period of April to July. Recently, significantly faster growth in temperate seabass juveniles (Lavergne et al. unpublished) and high population densities in Japanese eel (Harada et al. 2018) have been revealed in the Katsura River estuary, where well - balanced nutrient salts are supplied in adequately high concentration, compared to rivers where this is not the case.

In Kunisaki Peninsula, the nutrient salt cycle is characterized by dissolved nitrogen of high concentration that flows out of the forests of Mt. Futago. Unfortunately, the origin of this nitrogen is thought to be large cities that generate nitrogen compounds into the atmosphere. They are eventually transported and becomes trapped in forests. However, it is suggested that forests absorb nitrogen compounds and grow based on long - term recycling. Furthermore, we have revealed that excess nitrogen entering mountain streams is reduced through the traditional agricultural and irrigation systems of Kunisaki Peninsula, and that the sea is supplied with nutrient salts which is exquisitely balanced with the addition of phosphorus (Sugimoto et al. 2021). The environment and ecosystem are changing under the influence of human activities. Atmospheric nitrogen compounds are expected to decrease in the future. In order to track how the ecosystem will adapt to such changes, it is important to monitor the long - term nutrient cycle of agriculture and fishery in Kunisaki Peninsula.

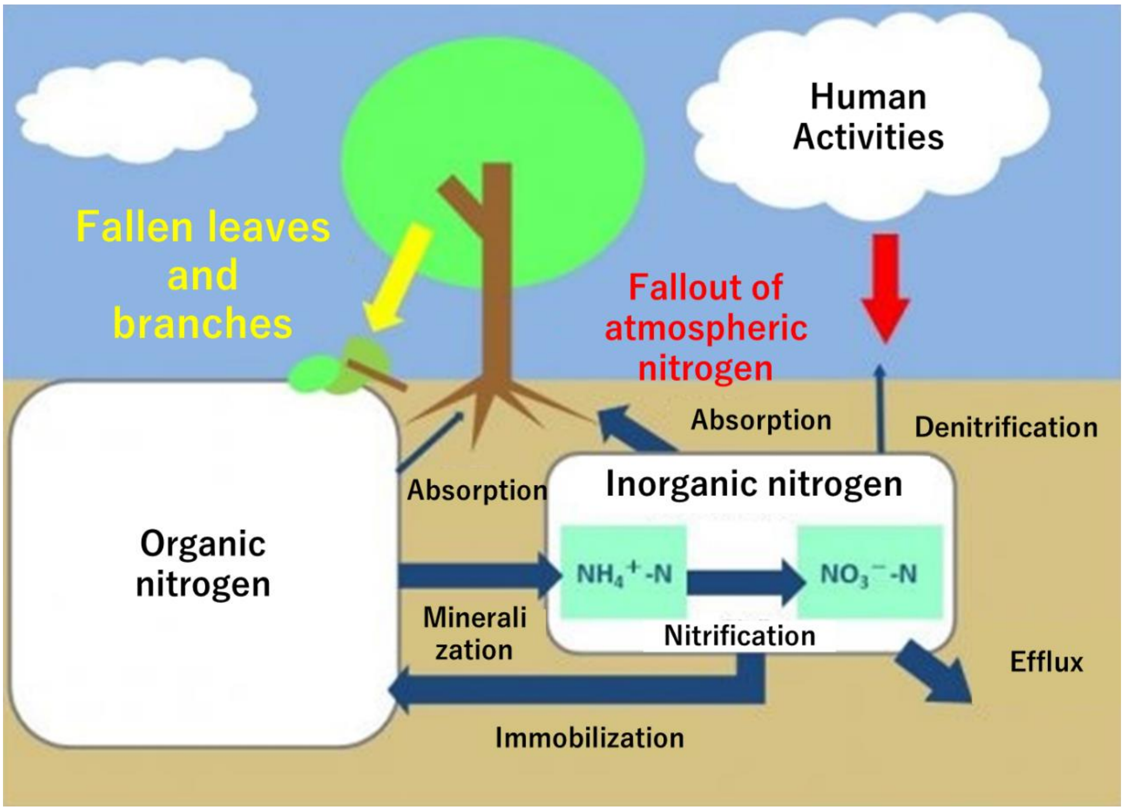

Figure 4. Nitrogen cycle and nitrogen saturation of forest ecosystems. (Adapted from Tateno 2014)

4. The role of iron in biological production of the sea

Alongside major nutrient salts of nitrogen, phosphorus, and silicon, trace elements (e.g. iron and zinc) are also important for the proliferation of aquatic plants including phytoplankton. Iron is especially essential for the survival of phytoplankton, since it is necessary for the electron transfer system of photosynthesis and the synthetic pathway of photosynthetic pigments. Iron can be dissolved in water in the form of ion (dissolved iron), which is easily utilized by aquatic plants including phytoplankton. However, dissolved iron is readily oxidized in water and forms hydroxides, which deposits and becomes unavailable to plants. Some offshore areas deficient in dissolved iron are known to be low in phytoplankton productivity (HNLC: high - nutrient low - chlorophyll areas). Experimental studies showed that addition of iron ions to such areas immediately increased phytoplankton. This has brought attention towards the role of dissolved iron in coastal areas as well.

When fallen leaves and branches accumulate and decompose on forest floors, they create anaerobic or reduced conditions. Under such conditions, dissolved iron and humic acid are produced to form iron humate (iron fulvate), which is not easily oxidized. When it leaks into rivers and eventually reaches the sea, it likely contributes to primary production in coastal areas. Some hypothesize that the deterioration of forests and consequent deficiency of iron humate are causing a reduction in biological production in coastal areas. This is one of the scientific theories supporting the forest planting activities by fishermen and citizens. Professor Shiraiwa and his research team investigated the nutritional relationship between the Sea of Okhotsk and Amur River, which runs in the border of Russia and China. They revealed that dissolved iron produced in the basin of Aumr River contributes significantly to the biological production of the Sea of Okhotsk and the neighboring Oyashio Current (Kuril Current) (Shiraiwa 2011). In contrast, dissolved iron is abundantly supplied from land to coastal areas in Japan, and thus it is said that insufficient dissolved iron rarely limits primary production in coastal areas.

To look into this in detail, we investigated the dynamics of dissolved iron in Yura River and Tango Bay (Watanabe et al. 2018). This research revealed that dissolved iron leaking from forests into rivers is minimal and much of the iron originates from agricultural fields and cities. Moreover, most of the dissolved iron transported by rivers (over 94%) is removed from the water column by deposition in the estuary (Fig. 5). These findings give us the impression that iron from forests does not contribute to the productivity of the sea. Thus, we investigated the form of iron in detail. This revealed that there are two forms of dissolved iron in river water: colloidal iron and iron humate. Our findings suggest that while colloidal iron is removed by deposition in the river mouth, iron humate is most likely transported to the sea. In other words, iron humate produced mainly in forests is the terrestrial iron that supports seaweed/seagrass beds and phytoplankton in the sea. So, is iron the main nutrient which influences primary production in Tango Bay? It may not be so simple.

When we apply the Redfield ratio, phosphorus is more deficient than iron in Yura River, and nitrogen is the most deficient nutrient in Tango Bay. However, when we conducted experiments by adding nutrient salts to the water of Tango Bay collected in different locations at different times, occasionally phytoplankton increased with the addition of iron (Watanabe et al. 2017). This indicates that iron can be more deficient than other nutrient salts in some situations. The role of dissolved iron in coastal primary production has been studied at several sites in Japan, but a clear deficiency of iron has not been reported yet. Though our study does not directly support iron deficiency either, it is important that our findings suggest that iron humate is produced in forests and transported downstream to potentially increase primary production in the sea. On the other hand, sea water in the northern Pacific coast, such as Tohoku and Hokkaido areas, has high concentrations of nitrogen and phosphorus. Iron may be relatively deficient in these areas, suggesting that iron could be the nutrient that determines primary productivity (most scarce nutrient). We are anticipating for more studies to be conducted in these areas. Research on the role of iron humate that is supplied from land to the sea has only just begun.

"Rich nutrients of forests nurture the sea" is a straightforward catch phrase which explains the mechanism of the CoHHO. However, the relationship between forests and the sea is not so simple from the point of nutrients. When we try and explain the importance of the connectivity from forests to the sea, we tend to focus on nutrients. However, there are many other factors which are just as important as nutrient supply. For example, some of such issues include the water retention function of forests and water discharge in rivers, as mentioned in the section 2 of this article. In the following article, I would like to consider factors other than nutrients.

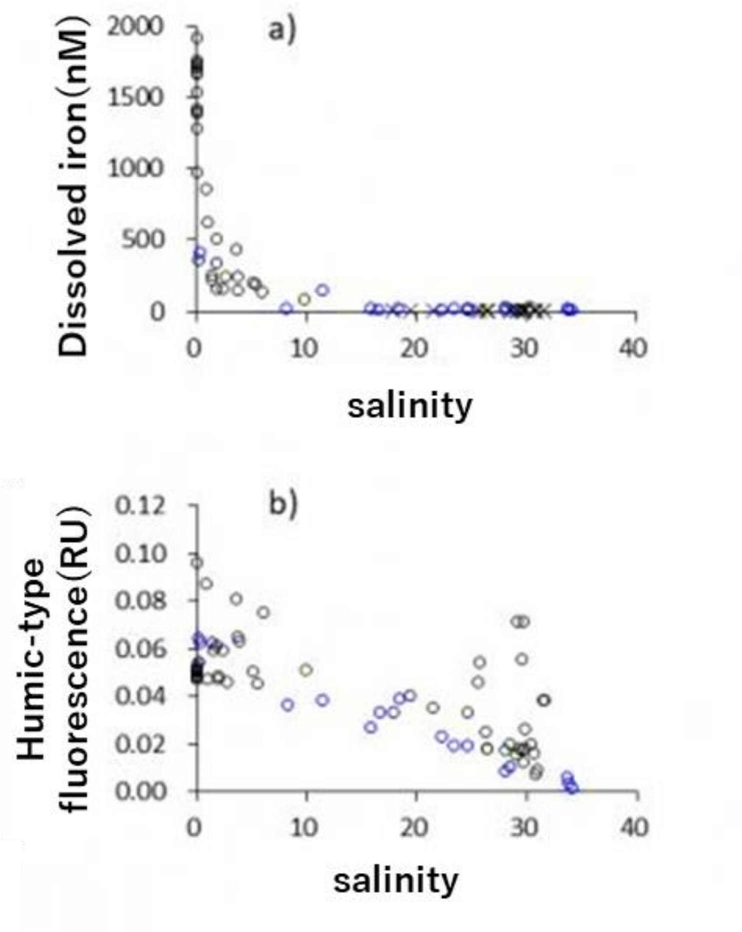

Figure 5. a) Change in dissolved iron (colloidal iron and iron humate) from river to coastal area. b) Change in humic - type fluorescence (indicator of iron humate) (Adapted from the figure of Watanabe et al. 2018).

Black circles indicate collected river water, **blue circles** indicate collected coastal water, crosses indicate below measurement limit. Most of dissolved iron considered as colloidal iron decreases drastically in river mouths (salinity <5), whereas humic - type fluorescent substance (including iron humate) does not deposit and dissipates in the sea.

Reference

Costanza, R. et al. 1997. The value of the world’s ecosystem services and natural capital. Nature, 387, 253 - 260.

Fukusaki et al. 2014. Distribution and dynamics of dissolved iron and dissolved organic matter in the Yura River basin. Annual Report of the Project for Creation of a Regional Recycling Wood Culture Society through CoHHO Studies, 2013, 73 - 97. (In Japanese)

Harada, M. et al. 2018. Japanese eel anguilla japonica and aquatic animals collected with Ishi - kura net in the Iroha and Katsura Rivers, Oita Prefecture, Japan. Nippon Suisan Gakkaishi, 84, 45 - 53. (In Japanese with English abstract)

Kasai, A. 2014. Ecosystem services from coastal areas. In Shimizu N. et al. eds., Connectivity of Hills, Humans and Oceans. Kyoto University Press. Kyoto. 178 - 184.

Kume, M. et al. 2021. Factors structuring estuarine and coastal fish communities across Japan using environmental DNA metabarcoding. Ecological Indicators, 121, 107216.

The Committee on Marine Environmental Issues of the Oceanographic Society of Japan 2008. Background of the proposal on Shitara Dam construction and river management in the Toyokawa River system: Necessity of environmental impact assessment and river management considering the connectivity between river basins and coastal waters. Oceanography in Japan, 17, 55 – 62. (In Japanese)

Shiraiwa, T. 2011. Uotukirin no Chikyu Kankyogaku. Showado, Kyoto. 1 - 226. (In Japanese)

Sugimoto, R. et al. 2021. Traditional land use effects on the magnitude and stoichiometry of nutrients exported from watersheds to coastal seas. Nutrient Cycling in Agroecosystems, 119, 7 - 21.

Tateno, R. 2014. Structure and function of forest ecosystems. In Shimizu N. et al. eds., Connectivity of Hills, Humans and Oceans. Kyoto University Press. Kyoto. 9 - 27.

Unoki, S. 2015. Morikawaumino - suikei - Keiseito - setudan - no - kyoui. Koseisha - Koseikaku, Tokyo. (In Japanese)

Watanabe, K. et al. 2017. Estuarine circulation - driven entrainment of oceanic nutrients fuels coastal phytoplankton in an open coastal system in Japan. Estuarine, Coastal and Shelf Science, 184, 126–137.

Watanabe, K. et al. 2018. Iron and fluorescent dissolved organic matter in an estuarine and coastal system in Japan. Limnology, 19(2), 229 - 240.

Yamamoto, T. 2007. Oligotrophication and changes of phytoplankton species composition in estuaries induced by dam construction. Nippon Suisan Gakkaishi, 73, 80 - 84. (In Japanese)

Yokoyama, H. et al. 2019. Spatial dietary shift of the intertidal snail *Batillaria multiformis*: stable isotope and gut content analyses. Plankton and Benthos Research, 14, 86 - 96.

Yokoyama, H. et al. 2019. Linkage between watershed and estuary estimated from the stable isotope analysis of the intertidal snail, *Batillaria multiformis*. Plankton Benthos Res 14, 97 - 104.