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A holistic solution to the polymer problem of the Anthropocene

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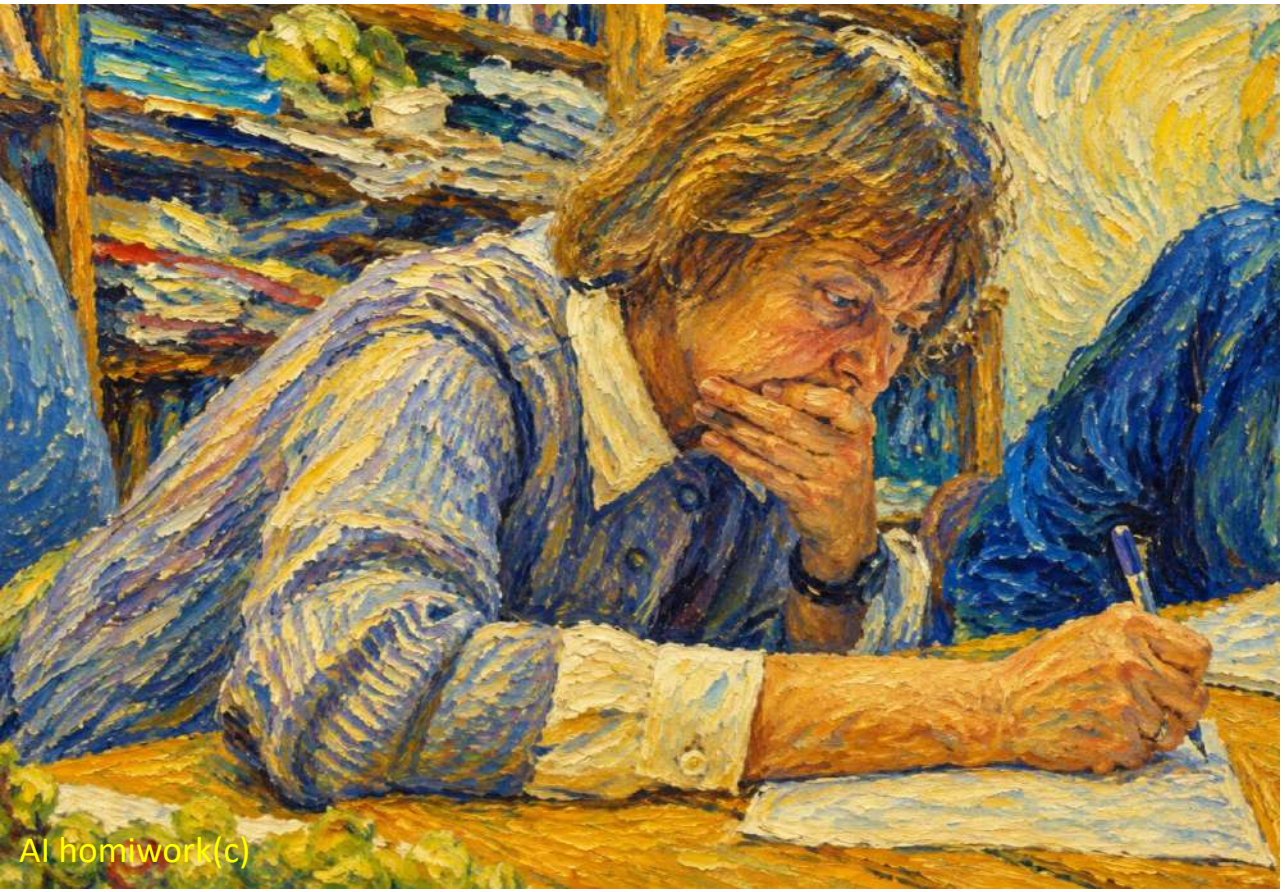
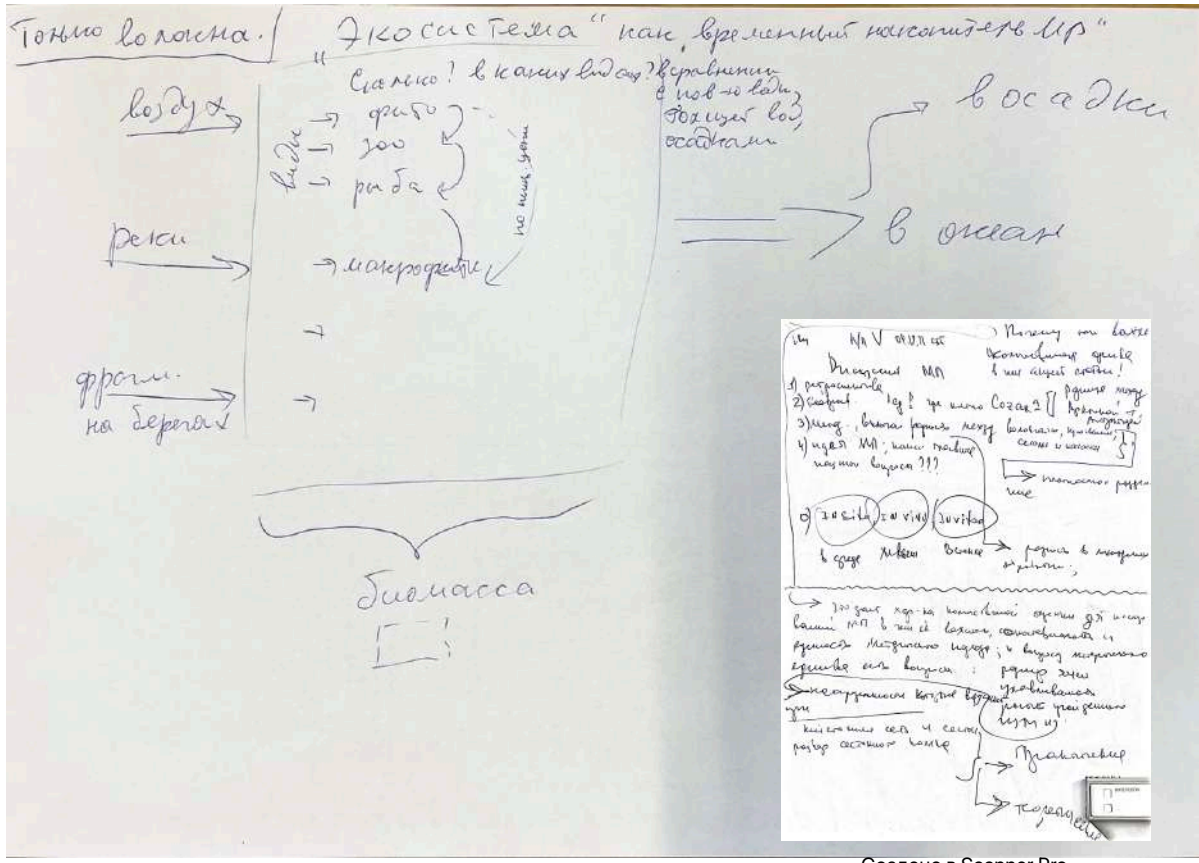
Acknowledgments





The authors honor and dedicate their work to the memory of the outstanding Irina Petrovna Chubarenko (†), with whom the original idea was discussed. Our human sympathies and scientific aspirations remain in her direction, continuing and developing her creative legacy.

Five theses. About the very basics.

- Plastic, Ecosystems and Populations
  - 14 and 86%
    - Science in the Emerging Paradigm
      - Plasticine Crow
        - Bridge to the Main

Thesis 1
Plastic, Ecosystems and Populations (?)

- Why 5 mm (?) Impact (and how much?) –
  - **MOSTLY NO** Senko et al., 2020 (47 populations);

    YES Lavers et al., 2026 (Birds);
    - Plastic pollution affects **all nine** planetary boundaries **ALREADY** of the Earth (Villarrubia-Gómez et al., 2024);
- The authors position is the "DO NO HARM" principle: the volumes of polymer production and products derived from them would be / should be / and MUST finally determined by the assimilation capacity of ecosystems.

Thesis 2 14% vs 86%

- Let’s All plastic in the ocean is 100%. Microplastics are about 14%. How is the remaining 86% accounted for?
    - The ecosystem knows no divisor. The entire mass is important. Therefore, whether it's a fiber, a bag, or a particle, it's all the same (except for hydrodynamic behavior and fouling effects).
        - What does it mean to count plastic (100%)?
- So, chasing 14% means we're missing 86%! It's unlikely that such priorities are correct.

Thesis 3. Science at the stage of paradigm formation

- Let us state that the study of plastics in the environment is a science. It's in the process of establishing a **paradigm**. Let's look at what happened to other fields (just three examples):
    - **Genetics** before Watson/Crick was a science, but without knowledge of DNA structure;
    - **Climatology** before Budyko had theory of heat balance;
    - **Conservation biology** emerged in the 1980s from the "green" movement, but has developed into a rigorous "crisis discipline" by combining mathematics and population genetics;
- Therefore, we say that Plastic in the Environment is a science. A paradigm? Our work is a step toward it.

Thesis 4. Off-top. Plasticine crow

- The "Plasticine Crow" metaphor: we’re wandering in morphological terms (nano-, micro-, meso-, macro-)
  - That metaphor fits into the concept of a geological Anthropocene.
    - A **mass balance** model for all types plastics by input/output flows is needed.



Thesis 5.
Bridge – transition to the main part

- Mass balance isn't new. Koelmans, Kaandorp, Harris… are the foundation. Our contribution is integration in;
  - Threefold Methodology. Aquatic Ecosystems. Biota within Them as an Active Agents of Plastic Transfer. Regions of Eurasia. Continental Model Concept. Assimilation Capacity. Elimination;
    - The Time for Synthesis of Data on These Processes Has Come;
      - Now pls. on to the Main Part -

Problem: The plastic paradox

- Plastic is a ubiquitous material of the Anthropocene;
  - The increase in production and discharge is not accompanied by a proportional increase in surface ocean concentrations;
    - “The plastic paradox of aquatic ecosystems” (c): the ocean “masks” the scale of pollution by distributing plastic in the water column, bottom sediments, littoral zones, organisms and biotic transfers;

The authors’ key questions: what volume of plastic release and discharge **will not lead to a loss of ecosystem stability**, how will it be distributed in them, and with what effects?

- Conclusion: perhaps a balance approach to valuations (1)!? and verification with *in situ* data(2)?!

- **But how to do (1) and (2)?**



В контурах сплошная линия: подтвержденная статистика (Достоверная); тире-точка: региональные, трудноверифицируемые оценки (Умеренно надежная); пунктир: экспертные оценки / экстраполяция (Ненадежная). Пиктограммы: www.thenounproject.com (2026)

Qualitative assessment of the reliability of the initial information; the role of *in situ*, *supra situ*, and *in silico* in increasing the accuracy of plastic assessments in ecosystems to a reliable level

Прим. авторов: заглавные буквы в названиях блоков соответствуют уровням информационной обеспеченности (I, II, III) в тексте. Интенсивность окраски стрелок пропорциональна качеству исходной статистики. Приведенные пиктограммы в Рис.1 заимствованы на условиях лицензии Creative Commons Attribution 3.0 (CC BY 3.0). Авторы пиктограмм: Arista Sepiana Dewi, Chandra Lesmono, Claire Jones, Eucalyp, Ferdian Mauladi Risiq, Fina Arwiana, Gan Koon Lay, Gung Yoga, IMG visual icons (студия), Lewen Design, Muhammat Sakirman, Omah Icon (студия), Rizki 2putri и др.

Three-fold* approach to its solution: *in situ* / *supra situ* / in silico

- ***In situ*** — field-based measurements in the water column, bottom sediments, and littoral zone;
  - ***Supra situ*** — (near) remote optical methods using computer vision and neural network algorithms (a term coined de novo by the authors);
    - ***In silico*** — mathematical modeling that closes the balance and extends estimates to inaccessible areas and periods;

- - Integration of the three approaches increases the accuracy of plastic estimates to a level comparable to direct accounting of production (striving for the ideal).

* Holistic

The concept of the **balance model** and its representation in **equations** (I) & flows (II)

- $M(t) = \iiint_{WE} F \; dV$ (1);
  - $\frac{dM}{dt} = \dot{M}_{load}(WE) - \dot{M}_{ab}(WE) - \dot{M}_{b}(WE)$ (1a);
    - $\lim_{(t\to\infty)} M(t) = 0$ (!ideal!) (2)

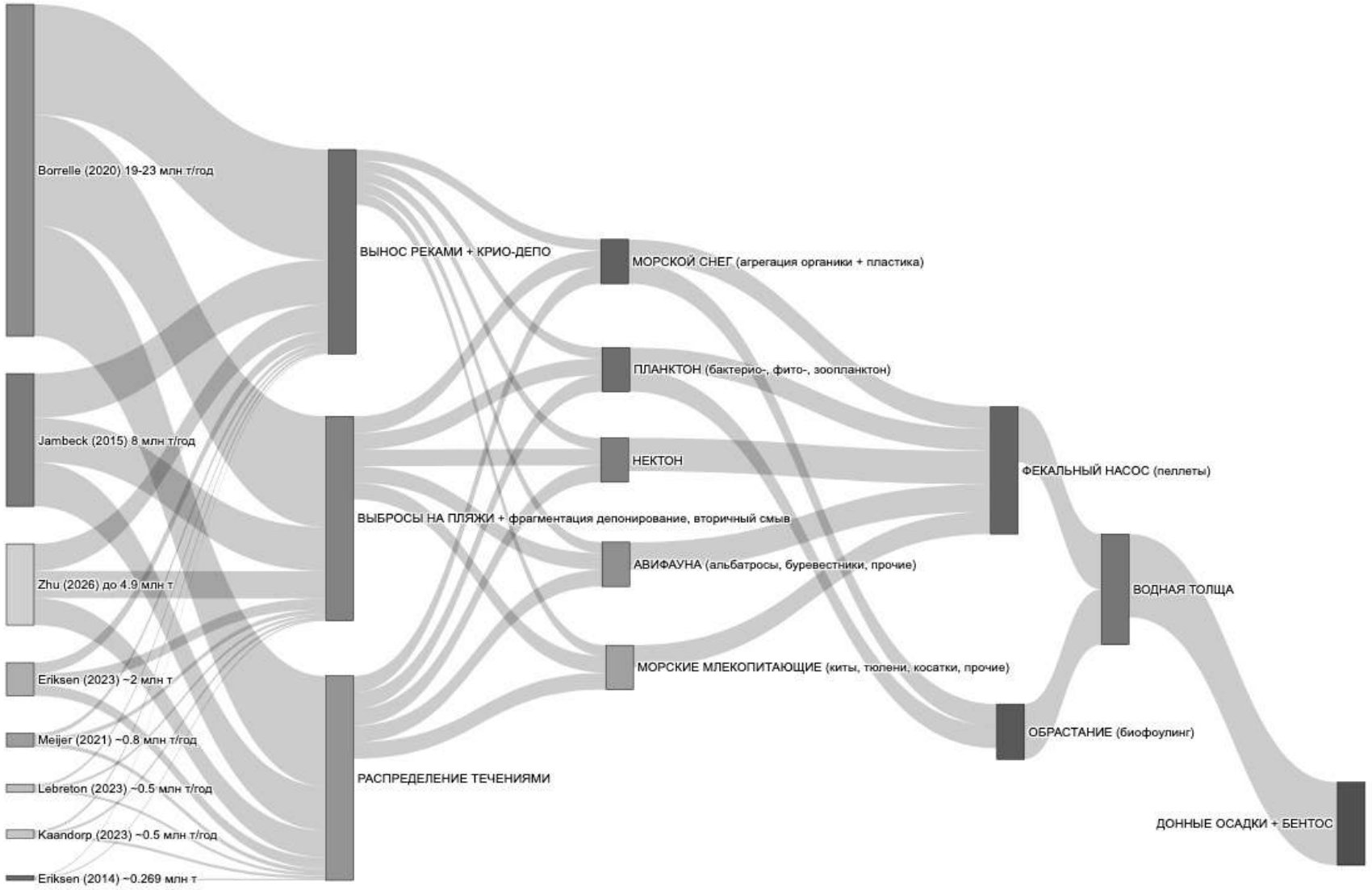
Now $M(t_i) > 0$, $t_i \in [1970,2019]$ (3)

equilibrium is broken by Eriksen et al., 2023 + new data available

(?Explanation available upon request!)

The flow scheme is robust to data deficiencies: the link topology and balance constraints transform gaps into a flow estimation problem

The concept of the balance model and its representation **in flows** (II)



Biota is an active agent, not just a passive reservoir.

- Biota doesn't just accumulate plastic—it transforms and transports it. The key biotic fluxes in equation (4) are:

$$\frac{dM}{dt} = \boldsymbol{R_{river}}(t) + A_{atm}(t) + T_{local}(t) - S_{sedim}(t) - C_{ocean_out}(t) - M_{beach}\ (t) - \boldsymbol{M_{plankton_bio}}(t) - \boldsymbol{M_{avifauna}}(t) - \boldsymbol{M_{nekton_mix}}(t) - \boldsymbol{M_{nekton_fish}}(t) - \boldsymbol{M_{mammals}}(t) \quad (4)$$

  - Pellet conveyor (+ fecal pump) + marine snow (twilight zone, abyssal zone) + biofouling + vertical movements – apparently the key mechanisms of vertical transport + advection… Plastisphere – new biotopes colonized by (micro)organisms;

    - Without parameterization of the biota, the model is not complete.

Therefore, we need to go to the Oceans, Rivers and Central Asia

- Oceans (North Atlantic, North Pacific, Western Arctic): this is where large accumulations of plastic form (**Cózar** Patch);

    - Lagrangian models have been tested, but biotic transfers are insufficiently accounted for;
        - Without ocean measurements, it is impossible to verify S_{sedim}), C_{ocean}, and M_{plankton};
            - Rivers (Ob, Yenisei (Angara), Lena, Amur, Volga, Don, Northwest (Neva, Pregolya, Northern Dvina)) are the main conduit for plastic entering the ocean; cryospheric transport and emissions are unique mechanisms not accounted for in global models; Without river data, the estimate of P remains uncertain by orders of magnitude;
            - Central Asia (Aralkum, Balkhash, Issyk-Kul) - Terminal basins – "dead ends" of continental runoff + Lake Khubsugul (Baikal)
        - Atmospheric transport from the dried bed of the Aral Sea and Central Asia – secondary sources of global pollution – (A_{atm}\) is underestimated / unclear.

Conclusion: the model **will not complete** without data for **all three geographies** (Oceans + Rivers + Deserts)

Which regions are ready for modeling?

The ranking was performed based on 11 components of equation (4)

Harrington verbal-numeric scale values and their interpretation for the purposes of verifying the balance flux model of plastic redistribution:

all-hands readiness 0.81–1.0;

high readiness 0.65–0.8;

moderate readiness 0.38–0.64;

low readiness 0.2–0.37.

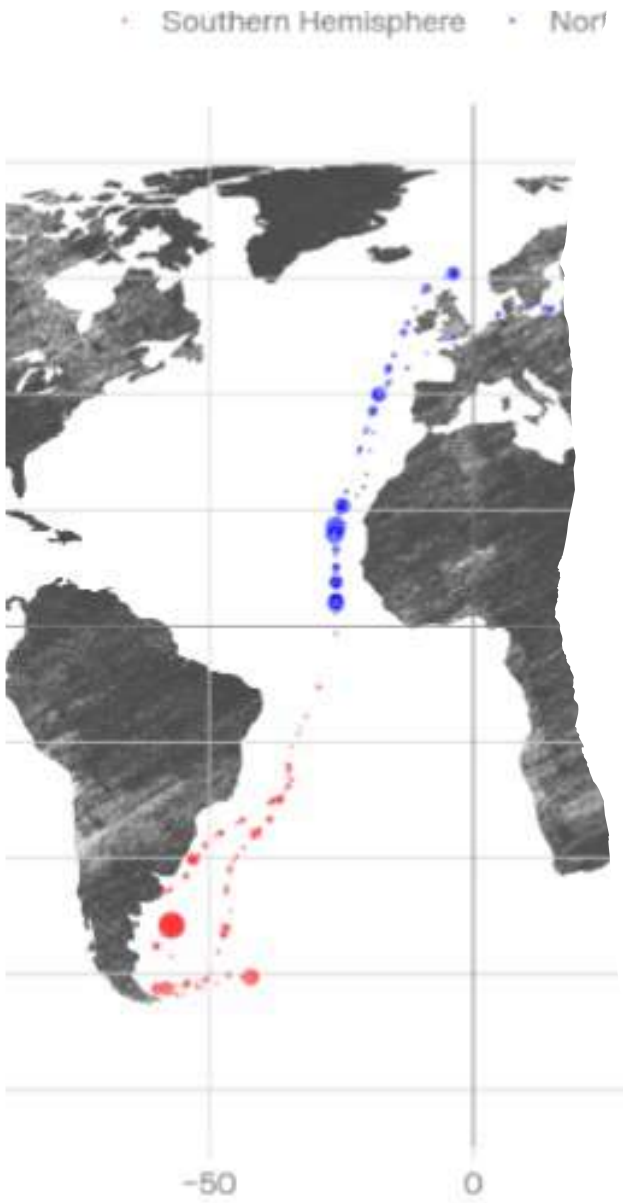
The **Cózar** is included in the North Atlantic.

The table reflects the concept's readiness for verification**, not its results**.

Место	Регион	Тип бассейна	Балл	Функция Харрингтона	Статус
1	Балтийское море	Замкнутые / полузамкнутые	49	0.89	Полностью готов
2	Северная Атлантика	Открытый океан	43	0.78	высокая готовность
3	Чёрное море	Замкнутые / полузамкнутые	40	0.72	высокая готовность
4	Баренцево море	Окраинные	37	0.67	высокая готовность
5	Нева	Реки	36	0.72	высокая готовность
6	Волга	Реки	35	0.7	высокая готовность
7	Северная Пацифика	Открытый океан	35	0.7	высокая готовность
8	Енисей	Реки	33	0.66	высокая готовность
9	Дон	Реки	33	0.66	высокая готовность
10	Обь	Реки	33	0.66	высокая готовность
11	Байкал	Озёра и водохранилища	32	0.64	средняя готовность
12	Японское море	Замкнутые / полузамкнутые	31	0.56	средняя готовность
13	Охотское море	Окраинные	29	0.52	средняя готовность
14	Онежское озеро	Озёра и водохранилища	29	0.58	средняя готовность
15	Северная Двина	Реки	27	0.54	средняя готовность
16	Ладожское озеро	Озёра и водохранилища	25	0.55	средняя готовность
17	Преголя	Реки	24	0.48	средняя готовность
18	Аралкум	Бессточные бассейны	19	0.38	средняя готовность
19	Иссык-Куль	Бессточные бассейны	19	0.38	средняя готовность
20	Хубсугул	Озёра и водохранилища	18	0.36	низкая готовность
21	Амударья	Бессточные бассейны	16	0.32	низкая готовность
22	Лена	Реки	14	0.28	низкая готовность
23	Балхаш	Бессточные бассейны	13	0.26	низкая готовность
24	Ангара	Реки	11	0.22	низкая готовность
25	Амур без Сунгари	Реки	11	0.22	низкая готовность

Supra situ - from Lagrangian to ecosystem *in silico*

- ***Supra situ***: from simple archives (GoPro, Floating Macro Litter JRC) to machine learning (MoCo, CatBoost, ADIS);
  - Lagrangian models are effective for hydrodynamic forecasting, but do not calculate the long-term fate of plastic;
    - Recommendations for ecosystem flow modeling: NEMURO (Kishi et al., 2007), ECOPATH (Polovina, 1984; Christensen, Pauly, 1992), ECOSIM (McMullen et al., 2024), EcoTracer (Serpetti et al., 2025);
- + models from the Institute of Mathematics and Mathematical Geophysics SB RAS (**Golubeva, Gradova, 2024a, b**);
- This allows us to link abiotic transfers with biotic transfers and quantify the assimilation capacity of the ecosystem ***in silico***



M***A***croplastic concentration, automatic camera monitoring along the route

RV Akademik Keldysh

2021-2022;

data from IPEE RAS, IO RAS, NPO DECO

(in arbitrary units, technology demonstration, 2026)

CONCLUSIONS

1. A paradigm for plastic distribution in ecosystems is emerging; the 5 mm size critea is likely **not ecologically supported**. Therefore, it is not "micro/macro before/after 5 mm," but the entire plastic continuum in the biotope-biocenosis-ecosystem nexus. This is the subject of current and future research;

2. In addition to abiotic impacts, **biota is an active agent** in both plastic transformation and transport. Without its parameterization, the balance model is incomplete. Numerical implementation proposes integrating the mass-balance model with NEMURO, ECOPATH/ECOSIM, EcoTracer, and similar approaches;

3. A three-component accounting methodology (***in situ***/***supra situ***/***in silico***) is substantiated;

4. **Priority regions**: Oceans (North Atlantic, North Pacific, Western Arctic), Rivers (Ob, Yenisei, Lena, Amur, Volga, Don), Central Asia (Aralkum, Balkhash, Issyk-Kul). Without them, equation (4) cannot be verified;

5. Without feedback **between monitoring, the turnover model, and materials science solutions, the polymer industry remains extensive**: output grows, but accumulation in ecosystems is unchecked. Quantitative assessment of flows is a prerequisite for regulating polymer production volumes and the transition to materials with controlled degradation.

PROSPECTIVES

Solaris=Pelagic Solaris + River Solaris + Desert Solaris

- **Solaris Project**. Focus on In Situ + Supra Situ + In Silico

- **Pelagic Solaris**. Going to the oceans. Not necessarily on huge ships.

Working **outside the EEZs**. This approach also allows for work in parts of the seas.

- **River Solaris**. New Hubsugul-Baikal + Angara. Lena, Amur! This will advance knowledge about the actual plastic content. It will provide a basis for accurate comparison. It will provide data for negotiations at any level. It will continue to influence the development of regulatory approaches to polymer production volumes.
  - **Desert Solaris**. Arid zones.

- **Questions about tolerances for determining assimilation and elimination are open.**
- **Methods for determining the age of plastics are open**.

- Let's not forget the final formula of our report:

In situ, Supra situ, In silico ≡ *Citius, Altius, Fortius* (6)

Here we should add: ***Sapientius*** (7)



Wisdom, 75+ age,
photo by Jon Plissner ©/USFWS

Grazie ·
Gracias ·
Merci ·
Thank you ·
Спасибо ·
· شكر
谢谢 ·
ありがとう