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Bioinspired Sentinels: The New Face of Environmental Intelligence

Environment * AI * Conservation

The Anthropocene Monitoring Paradox and Environmental Intelligence

In the Anthropocene, where human activity dominates planetary biogeochemical cycles, the escalating crises of biodiversity loss, chemical pollution, and climate change demand continuous, high-granularity monitoring that conventional instrumentation struggles to provide.[1] Traditional environmental sensing relies heavily on fixed meteorological stations or orbital satellite imagery -- approaches that are either too spatially sparse to capture local microclimate dynamics or too coarse to resolve sub-canopy and benthic processes.[1] Moreover, conventional in-situ sensors constructed from rigid synthetic plastics, heavy metals, and toxic chemical batteries risk contaminating the fragile habitats they are meant to safeguard.[1][2]

In response to this instrumental paradox, a transdisciplinary paradigm has emerged: Environmental Intelligence (EI). As synthesized in the landmark 2025 Annual Review of Control, Robotics, and Autonomous Systems analysis by Barbara Mazzolai, Cecilia Laschi, and Laura Margheri, EI integrates environmental science, robotics, data science, and artificial intelligence to build a systemic understanding of the biosphere.[1] This convergence directly underpins the global "One Health" framework, recognizing that human health, wildlife viability, and ecosystem integrity are inextricably linked.[1] Central to the physical execution of EI is Ecorobotics -- a design philosophy that replaces intrusive industrial machinery with bioinspired, energy-autonomous, and fully biodegradable sentinels engineered to operate within natural nutrient cycles and decompose harmlessly once their observational mission concludes.[1][2]

Phytomimetic Bioinspiration: Seed Aerodynamics, Hygroscopic Actuation, and Soft Continuum Robots

Whereas first-generation field robotics focused primarily on zoomorphic (animal-like) legged or wheeled platforms, the frontier of ecorobotics increasingly turns to the plant kingdom. Over billions of years of evolution, plants have mastered muscle-free actuation, distributed environmental sensing, and passive energy harvesting in unstructured terrain.[1][2] Coordinated by the Istituto Italiano di Tecnologia (IIT), the European I-Seed project exemplifies phytomimetic engineering by developing battery-free, biodegradable "artificial seeds" modeled on two botanical dispersal strategies:[3][4]

* Aerodynamic Autorotation (Acer campestre): The field maple samara utilizes an asymmetric mono-winged geometry that induces stable autorotation -- a helicopter-like spinning descent once studied by Leonardo da Vinci -- to lower terminal velocity and ride wind gusts over long distances.[3] By 3D-printing this exact aerodynamic profile from compostable biopolymers doped with environmentally

sensitive fluorescent dyes, researchers created passive flying sensors whose optical luminescence shifts predictably with surface temperature or chemical analytes.[3][4][5] Autonomous drones equipped with LiDAR and hyperspectral cameras then scan the landscape from above, reading out soil parameters optically without requiring onboard batteries, radio transmitters, or sensor retrieval.[3][5]

* Hygroscopic Drilling (Avena and Erodium): Wild oat (Avena) and stork's-bill (Erodium) seeds possess hygroscopic awns -- fibrous appendages whose tissues absorb atmospheric moisture differentially across diurnal humidity cycles, coiling and uncoiling to generate mechanical torque that drills the seed into soil crevices.[1][6] Researchers have harnessed this passive actuator to construct miniaturized, biodegradable hygroscopic "HybriBots" that traverse soil pores and anchor themselves autonomously.[1][6] This embodies morphological computation, embedding navigational intelligence directly into physical material deformation rather than silicon microprocessors.[1][2]

* Soft Continuum Manipulators: Inspired by plant tropisms (directional growth responses to light, water, or gravity) and climbing vines, soft continuum robots elongate and bend smoothly through congested environments such as coral reefs or dense forest understories, relying on compliant proprioception to intertwine with natural supports without damaging delicate organisms.[1][2]

| Design Dimension | | Conventional Robotics | | Ecorobotics |

| Materiality | | Rigid metals, non-degradable petroleum plastics | | Soft, compostable biopolymers (e.g., PLA, cellulose) |

| Energy Source | | Lithium batteries, fossil fuels | | Passive harvesting (wind, humidity), microbial fuel cells |

| Actuation | | Electric motors, high-pressure hydraulics | | Hygroscopic tissue deformation, pneumatic tropism |

| Lifecycle | | Persistent electronic waste (e-waste) | | Biodegradation and environmental integration ("leave no trace") |

| Control Logic | | Centralized silicon microprocessors | | Morphological computation & biohybrid signaling |

Material Innovation: Transient Electronics and General Shape-Changing Robots

Realizing "leave-no-trace" environmental monitoring demands a fundamental transition toward transient electronics and renewable structural polymers.[1] I-Seed fliers and drillers are fabricated from Polylactic Acid (PLA), a biocompatible polyester derived from fermented plant starch that provides the mechanical stiffness required for 3D printing before degrading via microbial hydrolysis in soil.[3][6] To eliminate persistent metallic circuitry, ecoroboticists are developing carbon-based conductive inks, edible plant-derived electrolytes, and circuit-free fluorescent optical reporters.[3][4] As outlined in the 2025 Annual Review, these advances point toward General Shape-Changing Robots (GSCRs): environmentally benign machines combining stretchable computing with robot-agnostic shape sensing to morph dynamically between snake-like conduits for subterranean navigation and flat sheets

for solar energy harvesting.[1]

Sentient Ecosystems: Aquatic, Terrestrial, and Biohybrid Case Studies

Across Europe, multi-institutional Horizon research consortia are translating Environmental Intelligence from laboratory prototypes into operational ecosystem monitors:

* SmartLagoon (Coastal Lagoon Digital Twin): Focused on Spain's Mar Menor -- Europe's largest saltwater coastal lagoon, severely threatened by agricultural runoff -- SmartLagoon couples SWAT and QWET hydrological transport models with AI-driven meteorological forecasting and citizen-science mobile reporting.[7][9][10] The resulting Digital Twin predicts dissolved oxygen drops, chlorophyll blooms, and eutrophication-induced anoxic episodes days ahead of mass fish mortality.[8][11]

* RAMONES (Abyssal Radioactivity Monitoring): Operating in high-pressure marine environments, RAMONES pairs static seafloor benthic laboratories with cooperative swarms of autonomous underwater gliders carrying low-power gamma-ray spectrometers to localize subseafloor radiation sources without endangering human divers.[12][13][14]

* ReSET (Nature-Based Spatial Intelligence): Combining open-source WaterWorld spatial hydrology software with low-cost, DIY FreeStation environmental loggers at the UK's Spains Hall Estate, ReSET quantified the performance of nature-based solutions -- specifically the reintroduction of beavers and leaky woody debris dams -- demonstrating their efficacy in attenuating downstream flood peaks and restoring soil moisture.[15][16][17]

* WatchPlant (Biohybrid Cyborg Flora): Rather than placing synthetic instruments beside vegetation, WatchPlant interfaces AI micro-transducers directly with living plants to decode sap flow and phloem electrical potential signatures under ozone pollution or drought stress, networking "cyborg plants" via ZigBee and LoRa protocols into a sentient urban forest.[18][19][20]

| Project | | Target Biome | | Core Technology | | Primary Environmental Innovation |

| I-Seed | | Topsoil & Air | | Biomimetic samara/awn robots | | Fluorescent battery-free sensing with drone LiDAR readout.[3][4] |

| WatchPlant | | Urban Forests | | Phyto-electronic biohybrids | | Living plants decoding pollution via electrical potentials.[18][19] |

| RAMONES | | Deep Sea | | Glider swarms & benthic labs | | Autonomous swarm localization of marine radioactivity.[12][13] |

| SmartLagoon | | Coastal Lagoon | | Hydrological AI Digital Twin | | Real-time anoxia forecasting & citizen science fusion.[7][8] |

| ReSET | | Watersheds | | WaterWorld & FreeStation | | Empirical verification of beaver dam flood mitigation.[16][17] |

Conclusion: A Symbiotic Planetary Nervous System

Environmental Intelligence and Ecorobotics mark a profound maturation in technological design -- acknowledging that rigid, waste-generating hardware cannot sustainably monitor a living planet.[1][2] Whether through a biodegradable seed that drills itself into topsoil, a soft continuum arm that navigates a coral reef, a coastal digital twin, or a network of biohybrid urban trees, these ecologically compliant systems blur the boundary between machine and organism, serving as a non-invasive nervous system to help diagnose and heal the Anthropocene biosphere.[1][20]

Updates... (Nov 19, 2026): Replaced inaccessible ResearchGate, conference-program, and broken institutional URLs with verified primary peer-reviewed DOIs for Environmental Intelligence, I-Seed, SmartLagoon, RAMONES, WaterWorld, and WatchPlant, and split grouped inline superscripts.

Works Cited

* [1] Mazzolai, B., Laschi, C., & Margheri, L. (2025). Environmental Intelligence and Ecorobotics: Toward Environmental Sustainability. Annual Review of Control, Robotics, and Autonomous Systems. https://doi.org/10.1146/annurev-control-030123-014212

* [2] Mazzolai, B., & Laschi, C. (2020). A vision for future bioinspired and biohybrid robots. Science Robotics. https://doi.org/10.1126/scirobotics.aba6893

* [3] Cikalleshi, E., Nexha, A., Kister, T., et al. (2023). A printed luminescent flier inspired by plant seeds for eco-friendly physical sensing. Science Advances. https://doi.org/10.1126/sciadv.adi8492

* [4] Istituto Italiano di Tecnologia (2023). The first eco-friendly fluorescent artificial seed for monitoring soil temperature by using drones. https://opentalk.iit.it/en/the-first-eco-friendly-fluorescent-artificial-seed-for-monitoring-soil-temperature-by-using-drones/

* [5] Leibniz Institute for New Materials (2023). Acer I-Seed: the first eco-friendly fluorescent artificial seed for monitoring soil temperature by using drones. https://www.leibniz-inm.de/en/press-releases/19149/

* [6] Mariani, S., Cecchini, L., Pugno, N. M., et al. (2023). An autonomous biodegradable hygroscopic seed-inspired soft robot for visual humidity sensing. Materials & Design. https://doi.org/10.1016/j.matdes.2023.112408

* [7] European Commission CORDIS (2025). SMARTLAGOON: Innovative modelling approaches for predicting Socio-environMentAl evolution in highly anthRopized coasTal LAGOONs (Grant 101017861). https://cordis.europa.eu/project/id/101017861

* [8] UCAM Catholic University of Murcia (2024). The SMARTLAGOON project presents the digital twin of Mar Menor. https://international.ucam.edu/university-news/smartlagoon-project-presents-digital-twin-mar-menor

* [9] European Citizen Science Platform (2024). SMARTLAGOON Project Profile. https://citizenscience.eu/project/335

* [10] Senent-Aparicio, J., L pez-Ballesteros, A., Nielsen, A., & Trolle, D. (2021). A holistic approach for determining the hydrology of the Mar Menor coastal lagoon by

combining hydrological & hydrodynamic models. Journal of Hydrology. https://doi.org/10.1016/j.jhydrol.2021.127150

* [11] Gim nez, J. G., Granero, A., Senent-Aparicio, J., et al. (2024). Assessment of oceanographic services for the monitoring of highly anthropised coastal lagoons: The Mar Menor case study. Ecological Informatics. https://doi.org/10.1016/j.ecoinf.2024.102554

* [12] Mertzimekis, T. J., Nomikou, P., Petra, E., et al. (2021). Radioactivity Monitoring in Ocean Ecosystems (RAMONES). Proceedings of the Conference on Information Technology for Social Good. https://doi.org/10.1145/3462203.3475906

* [13] DeepSync (2024). RAMONES Project Fact Sheet. https://deepsync.eu/project/ramones/

* [14] PLOATECH (2024). RAMONES Marine Radiation Monitoring System. https://ploatech.com/projects/ramones/

* [15] Mulligan, M. (2012). WaterWorld: a self-parameterising, physically based model for application in data-poor but problem-rich environments globally. Hydrology Research. https://doi.org/10.2166/nh.2012.217

* [16] European Commission (2021). HORIZON2020 -- How to help ReSET economy and environment through spatial planning. https://ec.europa.eu/newsroom/horizon2020/items/698436

* [17] European Commission Directorate-General for Environment (2025). ReSET for the Future. https://environment.ec.europa.eu/news/reset-future-2025-04-09_en

* [18] Hamann, H., Bogdan, S., Diaz-Espejo, A., et al. (2021). WatchPlant: Networked Bio-hybrid Systems for Pollution Monitoring of Urban Areas. The 2021 Conference on Artificial Life. https://doi.org/10.1162/isal_a_00377

* [19] Garc a-Carmona, L., Bogdan, S., Diaz-Espejo, A., et al. (2021). Biohybrid systems for environmental intelligence on living plants. Proceedings of the Conference on Information Technology for Social Good. https://doi.org/10.1145/3462203.3475885

* [20] European Commission CORDIS (2025). WATCHPLANT: Smart Biohybrid Phyto-Organisms for Environmental In Situ Monitoring (Grant 101017899). https://cordis.europa.eu/project/id/101017899/results