Bio-Digital Resilience: Integrating Biomimicry and Artificial Intelligence for Next-Generation Disaster Prediction and Recovery Systems

B. Mohan Krishna Reddy
Affiliation:- St. Joseph's Convent Senior

Abstract

Most current infrastructures for disaster management rely on satellite-centred, centralized AI systems. These systems have meant demonstrated high-resolution monitoring systems for a long time. Still, these systems are not robust to the mimicking of data bottlenecks, fragile infrastructures, and solely working in linear ways under extreme stress (central risk). We presented a biomimetic resilience framework inspired by ecological systems (mycorrhizal fungal networks, swarm intelligence of ants, and distributed neural networks of octopuses) to create adaptive, decentralized, and self-healing AI ecosystems for disaster prediction and recovery.

Different from a conventional paradigm of satellites, simulating an extreme disaster implies we can have an adaptive multi-agent network across land, air, sea, and the binary systems we can create around behavior. These bio-inspired systems demonstrate resilience by dynamically reallocating resources, self-healing through redundancy, and evolution through feedback loops to propose applicable case studies (wildfire containment, urban inundation/flooding, and post-earthquake recovery) of biomimetic AI to real world challenges.

The paper also combines ethical design principles, based on ecological balance and cultural inclusion, to ensure that AI-centric systems foster human trust and do not perpetuate anthropocentric biases. In contrasting bio-digital resilience with satellite-based disaster intelligence, we articulate a paradigm shift away from robust mechanical systems to "living" AI architectures, which favor adaptability, diversity, and situational awareness.

This synthesis takes the first steps toward the design of new disaster management systems, enabling organizers - from policymakers and engineers to scholars and academics - to design disaster-resilient societies that evolve with, not against, nature.

Keywords: Biomimicry, Disaster management, Artificial Intelligence, Resilient systems, Swarm Intelligence, Mycorrhizal Networks, Self-healing architectures, Ecological AI, Decentralization, Adaptive Recovery, & Ethical AI

1. Introduction

1.1 The Intensifying Need for Disaster Resilience

Disasters, whether natural or human-induced are becoming more numerous, more intense, and affect more people on the global scale. The United Nations Office for Disaster Risk Reduction (UNDRR) states that over the past 2 decades, over 4 billion people have been affected by disasters and global economic losses were in excess of $3 trillion. Climate change is serving to compound these trends, increasing the probability and severity of floods, droughts, wildfires, and cyclones.

Current disaster management models rely overwhelmingly on centralized infrastructures, large-scale satellites, national control

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centers, and global databases. These systems are powerful yet susceptible to structural flaws: single point failure (SPF) problems, delays in decision making, and reliance on constant connectivity. In some instances, the disaster can even disrupt
the infrastructures that the centralized models depend on in order to operate.

1.2 The Limits of Satellite-Based Models

Recent technology (e.g., NASA–ISRO's NISAR satellite) has shown the capabilities of integrating satellite use and AI for disaster prediction. They have global coverage, provide high-resolution observations of the Earth, and can quickly detect hazards with incredible detail and scale. However, they remain fundamentally top-down. The reliance on centralized data
through a data pipeline or ground stations means when the infrastructure cannot provide data that expect to receive in response, through earthquakes, hurricanes, or cyber-attacks; then this data will not be of use.

Additionally, satellite-based AI models are also subject to data overload. Most missions will collect terabytes of information daily. For local "end-users," this is a backlog that they will have to wait for a processing pipeline to respond, potentially delaying life-saving decision-making or deployments.

1.3.Biomimicry as an Model for Resilient AI

Nature provides decentralized, adaptive intelligence over billions of years rather than central engineering. Biological systems demonstrate resilience by not exclusively preventing failures but also absorbing and adapting, and evolving through disruption. For instance:

- Mycorrhizae fungal networks share resources between trees that are stressed.
- Ant colonies use decentralized, collaborative decision-making to survive.
- Octopusesdemonstrate distributed intelligence through semi-autonomous neural clusters in each arm.

This paper advocates a Bio-Digital Resilience Framework (BDRF) that uses biomimetic principles to create self-healing, adaptive AI systems as a way for predicting, preparing, planning, and responding to and recovering from disasters. Instead of resisting disruption
through redundancy, bio-inspired systems can focus on adaptability, diversity, and ecosystemic balance to facilitate resilience.

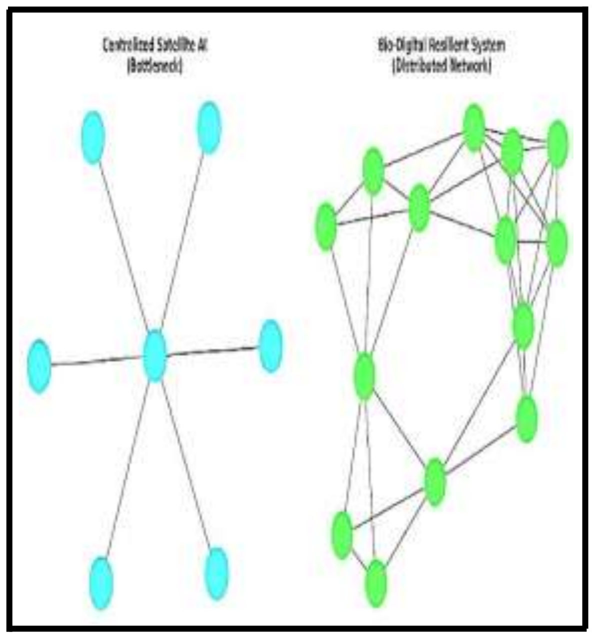

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Fig.1. Contrasting Centralized Satellite AI (left) with a Bio-Digital Resilient System (right).

2. Literature Review: From Mechanical Robustness to Ecological Intelligence

2.1 Classical Resilience in Engineering Systems

Engineering resilience has conventionally drawn from redundancy, robustness, and reliability. For instance, reliance on redundancy in engineering resilience can be found in high-reliability industries, like aviation and nuclear power generation, with multiple paths to safety and implementing stringent fault-tolerant structures. Reliably achieving redundancy and robustness adds energy and infrastructure costs and not flexible for stressors that have not been previously intended for design consideration.

2.2 Satellite and AI in Disaster Management

Recent literature recently highlights satellite–AI integration for global hazard assessment. Some highlights include:

- Incorporation of Synthetic Aperture Radar (SAR) for real-time, all weather monitoring.
- Application of Machine Learning (ML) in analysing predictive analytic sources.
- Use of Multi-agent systems for coordinating disaster recovery.

While these computer infrastructures are essential for improving aspects of early warning
systems and situational awareness, these systems rely heavily on centralization for high order coordination and therefore loses adaptability for use in field.

2.3 Biological Models in AI and Complex Systems

Biomimicry is now impacting robotics, materials science, and networks. Some examples include:

- Swarm robotics based on ants to minimize paths.
- Fungal-based networks as paradigms for resilience in computational routing.
- Neural plasticity and other architectural paradigms to improve adaptive AI.

However, we are aware that biomimicry has not been systematically applied to disaster management, and this study represents the first step in that direction, a novel

Dimension	Classical Engineering	Ecological Biomimicry
Redundancy	Duplicate Components	Distributed Adaptability
Recovery	Repair/Replace	Regeneration/Self Healing
Control	Centralized	Decentralized
Efficiency	High-cost Safety	Resource-efficient
Learning	Fixed Protocols	Continuous Evolution

Table 1. Classical vs. Ecological Approaches to Resilience

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3. Methodology

3.1 Research Design

This article uses a conceptual systems-engineering lens based on biomimicry and complex adaptive systems to create a Bio-Digital Resilience Framework (BDRF) that integrates ecological models, AI architecture, and disaster management case studies.

3.2 Analytical Dimensions of Resilience

Based on resilience engineering literature, we consider systems from five perspectives:

1. **Robustness** - the ability to withstand stress.
2. **Adaptability** - the ability to develop under new conditions.
3. **Recoverability** - the ability to be restored quickly.
4. **Scalability** - the ability to expand/contract the use of resources as needed.
5. **Sustainability -** the ability to sustain function without ecological or social harm.

3.3 Data Sources

The analysis draws from literature across systems engineering, AI, ecology, disaster management, and ethics. The analysis combines peer-reviewed literature from 2015-2025 and ecological field studies and serves as the basis for this interdisciplinary review.

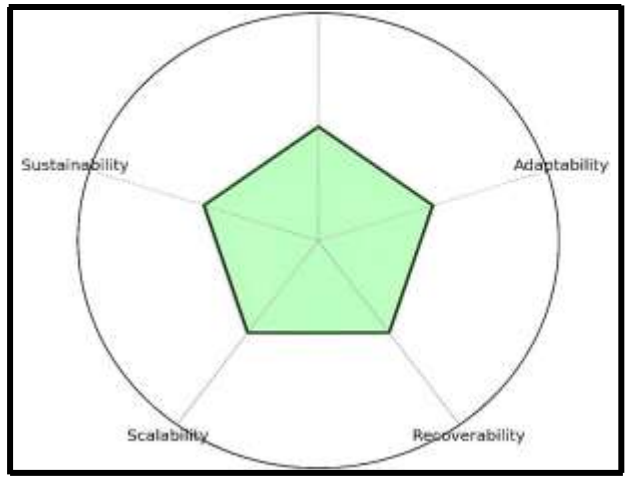

Fig.2. Analytical Axes of Bio-Digital Resilience.

4. The Bio-Digital Resilience Framework (BDRF)

4.1 Mycorrhizal-Inspired Resource Redistribution

In forests, mycorrhizal fungal networks facilitate trees to share carbon, water, and nutrients, and similarly in disaster AI networks, nodes are able to redistribute computing, storage, and energy resources based on signals of stress. That means that if a nearby sensor network in a floodplain were overwhelmed, other nodes could route power and data to stricken areas to maintain coverage automatically.

4.2 Swarm Coordination Inspired by Ant Colonies

Ant colonies are incredibly good at coordination with a small number of local rules including pheromone trails, redundancy in worker roles, and flexible labor allotment while dynamically reorganizing roles and labor. In the BDRF, UAVs (drones), IOT devices, and Robots on the

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ground are able to use stigmergic algorithms that build in swarm style organization to self-organize the guidance of evacuations, seek and rescue, and supply delivery.

4.3 Distributed Intelligence Inspired by an Octopus

An octopus's arms each contain a small, independent cluster of neurons, therefore their arms can behave autonomously. Drawing inspiration, the BDRF deploys semi-autonomous local AI agents to support ongoing decision-making within the disaster zone that can make micro-decisions in real time, i.e. rerouting traffic around downed infrastructure, without waiting for instructions from a central server.

4.4 Feedback Loop in the Ecology

The ecology is adaptive through feedback loops (examples: predator–prey cycles, forest succession, etc.) while the BDRF closely integrates feedback from citizens, responders, and
sensors from the environment as an input to AI decision-making and allows the systems to learn as they evolve.

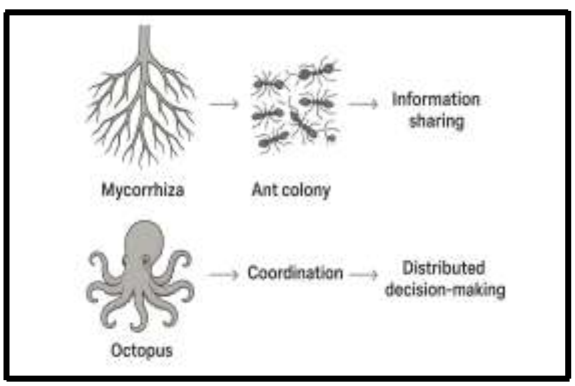

Fig.3. Biological Inspirations for Bio-Digital AI.

5. Case Studies: Conceptual Applications

5.1 Wildfire Containment

- **Problem**: Wildfires can spread at unpredictable rates and overwhelm centralized coordination of firefighting efforts.

- **BDRF Solution**: Drone swarms can apply retardants while using Stigmergic path-finding and ability to reroute dynamically for barriers. Power distribution can be organized by networks modeled after mycorrhizae that can push power into the most threatened areas. Semi-autonomous drones using octopus inspired strategic adjustment can be flexible to follow the fire and wind patterns. No need to mobilize to change reorganization
commands globally.

5.2 Urban Flooding

- **Problem**: Flooding can take down electrical grids and overwhelm centralized pumping systems.

- **BDRF Solution**: Smart pumps use fungal network power distributions, drones facilitate evacuation using ant organizing logic, and AI agents can use octopus logic to reorganize public transportation services. Data from citizens' phones serve as citizen generated feedback to adapt eco-socially and evolve patterns of response.

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5.3 Post Earthquake Recovery

- **Problem**: Collapse of infrastructure can stop the ability to centralize communications.
- **BDRF Solution**: UAV swarms create their own self-healing mesh networks, Ground robots autonomously clear debris; distributed AI agents reorganize medical supply delivery in a world where ecological feedback loops are adapting as roadways change.

Disaster Type	Challenge	Biomimetic Mechanism	Expected Benefit
Wildlife	**Rapid spread**	**Swarm drones (ants)**	**Dynamic containment**
Flood	**Power/Pump failure**	**Fungal redistribution**	**Maintain local capacity**
Earthquake	**Network collapse**	**Octopus intelligence**	**Local autonomous recovery**

Table 2. Conceptual Case Studies under BDRF

6. Comparative Analysis

Attribute	Satellite-Centric AI	Bio-Digital Resilience (BDRF)
Architecture	Centralized	Decentralized, Distributed
Adaptability	Fixed Models	Continuous learning
Failure Modes	Single-point Collapse	Self-healing
Scalability	Global but Rigid	Modular, expandable
Ethics	Anthropocentric	Ecological inclusivity
Response Speed	Delayed	Local real-time

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Table 3. Satellite-Centric vs. Bio-Digital Frameworks

7. Ethical & Socio-Technical Considerations

7.1 Ecological Balance Principle

BDRF systems prevent over-intervention that would lead to destabilizing ecosystems. For example, wildfire AI weighs the value of suppression against the restored natural cycles of regeneration.

7.2 Cultural Inclusivity

Emergency communication must be linguistically and culturally sensitive. Noting the limitations of AI translation, systems must create instances for cultural tailoring through engagement with local leaders who give credibility to these messages within their community.

7.3 Bias and Equity

The potential for bias in AI could result in genuinely excluding vulnerable populations. The use of biomimicry principles of diversity suggests that datasets should be varied and pluralistic to avoid dominating datasets and algorithmic monoculture which will only serve to segregate and limit choices and fairness of systems.

7.4 Trust and Transparency

Resilience, like ecosystems, depends upon networks of trust. AI systems must enable explainability and transparency which legitimizes their suggestions and transparency to citizens and responders.

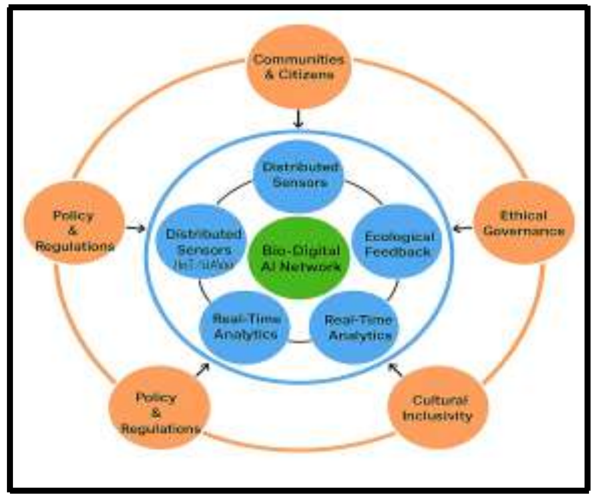

Fig.4.Socio-Technical Ecosystem of Bio-Digital Resilience.

8. Discussion

The BDRF framework represents a complete shift:

- From mechanical robustness (withstand failure with redundancy) → to ecological resilience, (adapt, evolve, regenerate).
- From centralized intelligence → to distributed intelligence based on natural systems.
- From anthropocentric design → to ecological ethics embedded within AI governance.

This does not replace satellite systems, it augments them to produce hybrid ecosystems in which global satellite data is combined with local adaptive biomimetic AI agents

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9. Conclusion

In this article, We have proposed a Bio-Digital Resilience Framework (BDRF) that leverages biomimicry with AI to develop disaster-management systems that are decentralized, reiterative, and ethical, facilitating community usage of bio-inspired AI to plan for, respond to, and adapt to disruptions with nature's recommendations. The structure of the BDRF, with inspiration from fungal, insect, and cephalopod intelligence, facilitates self-healing architecture, real-time ecologically distributed decision-making, and ecologically orient the governance of those systems.

Future research can support pilots deploying bio-inspired AI networks for disaster resilience, establish formal inter-operational relationships with ecologists, and develop "living AI ethics" that define community resilience for more vulnerable groups or communities.

If humanity can learn from the intelligence of nature, we have the opportunity to re-engineer, not just build, a disaster management system that can withstand adversity, but also thrive in adversity as a living relationship with the environment, rather than a disrupted disaster centre or system.

That can build communities of disaster resilience who engage with adverse conditions, rather than a reactor to disaster.

Data Availability

All data generated or analysed during this study are included in this published article

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