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PERSPECTIVE

When digital technologies stumble: Exnovating for conservation science and practice

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Abstract

Digital technologies are rapidly transforming conservation efforts in response to pressing planetary environmental challenges. However, these expanding innovations also introduce significant risks and failures that can deepen existing injustices. Although growing approaches to responsible innovation establish ethical standards and best practices for conservation technologies, gaps remain in addressing limited and obsolete methods. This perspective article presents the integration of exnovation strategies into conservation science and practice as a set of deliberate efforts to mitigate, diagnose, repair, remove, and substitute misaligned, ineffective, or harmful technologies. We propose exnovation interventions not only to address technological shortcomings but also to open space for responsible innovation pathways that foster negotiation, reflexivity, and context-sensitive approaches. These insights highlight the need for collaboration, the redistribution of accountability, and participatory engagement to ensure conservation technologies are responsive to local realities and diverse capabilities.

KEYWORDS

conservation justice, conservation technologies, exnovation, participatory methods, responsible innovation

1 | INTRODUCTION

Advancements in digital technology are driving groundbreaking biodiversity conservation efforts in response to global environmental challenges (Adams, 2019; Sandbrook, 2025). International policies have endorsed technological solutions as core strategies to accelerate the pace and scale of achieving ambitious conservation commitments, such as the Kunming-Montréal Global Biodiversity Framework (CBD, 2022). A wide range of conservation researchers, practitioners, policymakers, and communities increasingly engage with digital tools, including hardware devices, software platforms, and big data infrastructures (Lamba et al., 2019). Across various conservation applications, these digital technologies include spatial-prioritization models (Hanson et al., 2023), remote sensing for habitat monitoring (Young et al., 2022), biodiversity data platforms (Westerlaken, 2024), and a growing array of artificial intelligence (AI) tools (Reynolds et al., 2025), ranging from automated wildlife-image classifiers (Kwok, 2019) to chatbots that elicit expert knowledge (Sworna et al., 2024). Although these expanding digital practices offer notable opportunities to support informed conservation decisions, significant challenges persist in managing and addressing technological risks and failures.

Repurposed from agriculture, forestry, and security industries, these digital practices are entering diverse conservation sites, raising questions about their suitability and long-term impacts (Gabrys et al., 2022; Nitoslawski et al., 2021). These quick innovation cycles reflect the “move fast and break things” ethos of big tech firms, prioritizing development goals and economic gains over reliability and contextual appropriateness (Taplin, 2017). Although digital applications inherently present glitches when adopted in complex settings (Searle et al., 2024), there have been cases where technological tools led to critical failures and harms, ultimately making conservation efforts less equitable, inclusive, or beneficial (Duffy et al., 2019; Fleischman et al., 2022; Simlai & Sandbrook, 2021). Technological limitations can arise from the materiality of devices, or the underlying data and modeling processes (Nost & Goldstein, 2022; Sarkar & Chapman, 2021; Szetey et al., 2025). These shortcomings give rise to multiple forms of conservation injustices (Pritchard et al., 2022), including biased data-driven decisions (e.g., Chapman et al., 2024), invasive surveillance techniques (e.g., Goldstein & Faxon, 2022), bogus AI-generated evidence (e.g., Urzedo et al., 2024), and electronic waste impacts (e.g., Maffey et al., 2015). While expanding ethical principles strive to ensure that conservation best practices mitigate technological risks (e.g., Sandbrook et al., 2023; Sharma et al., 2020), glitches can also enable emancipatory interventions, widening the range of voices and perspectives shaping innovation (Leszczynski & Elwood, 2022).

The ambivalence of digital technologies lies in their potential to either support or undermine conservation aspirations and goals, depending on how these innovations are embedded within specific locations, socio-cultural contexts, and political arrangements (Bakker & Ritts, 2018; Millner & Amador-Jimenez, 2024; Turnbull et al., 2023). Increasing attention has turned to reenacting technological trajectories through institutional changes, participatory design, and context-responsive approaches that reflect local realities and capabilities (Luque-Ayala et al., 2024; Urzedo et al., 2025). Aligned with responsible innovation strategies, exnovation emerges as a central mechanism for interrogating and deliberately phasing out misaligned, limited, or detrimental technologies (Davidson, 2019; Holbek & Knudsen, 2020). In this perspective article, we present four interrelated strategies for enacting exnovation within conservation science and practice, including mitigating, diagnosing, repairing or removing, and substituting and adjusting technological concerns. These strategies support the operationalization of exnovation as an approach to responsible conservation efforts, contributing to context-sensitive pathways that value diverse forms of expertise and enable collaborative practices.

2 | EXNOVATION OF CONSERVATION TECHNOLOGIES

Recognizing the risks associated with emerging technologies has prompted a shift toward responsible innovation that accounts for ethical standards, public interest, and context-specific needs (Malakar & Lacey, 2024). In conservation, ongoing justice debates are reshaping the governance of data-driven research and practice (Robinson et al., 2023), while also boosting procedures for supporting digital accessibility, local capabilities, and the ethical deployment of technologies (Tabor et al., 2025; York et al., 2023). Emerging guidelines and codes of conduct offer best practices for the use of conservation technologies (Millner et al., 2023; Sandbrook et al., 2021), including the adoption of remote sensing technologies (e.g., Sharma et al., 2020; Young et al., 2022) and social media data (e.g., Di Minin et al., 2021). Ethical considerations also include open-source practices (Hsing et al., 2024), Indigenous data sovereignty principles (Jennings et al., 2023), and participatory approaches that govern the interconnections between community groups, locations, and diverse entities (Westerlaken et al., 2023). While current conservation protocols and standards rightly prioritize consultation, consent, and privacy to guide responsible technological practices, the evolving nature of digital developments demands greater attention to their potential consequences across diverse contexts.

Exnovation strategies offer tools to anticipate and manage technological challenges, support creative adaptation, and facilitate transitions toward contextually appropriate technologies (Arne Heyen et al., 2017). Originally, the term exnovation described discontinuing outdated, bureaucratic procedures (Yin, 1979) and the substitution of obsolete equipment to enable novel technologies (Kimberly, 1981). More recently, exnovation strategies have gained attention as key components for facilitating sustainability transitions (David & Gross, 2019), addressing complex socio-economic and political transformations (Davidson, 2019; Fuchs & Ziegler, 2024; Graaf et al., 2021). When applied to conservation science and practice (Figure 1), exnovation offers a valuable opportunity to expand responsible innovation pathways that emphasize anticipation, reflexivity, inclusion, and responsiveness (cf. Stilgoe et al., 2013).

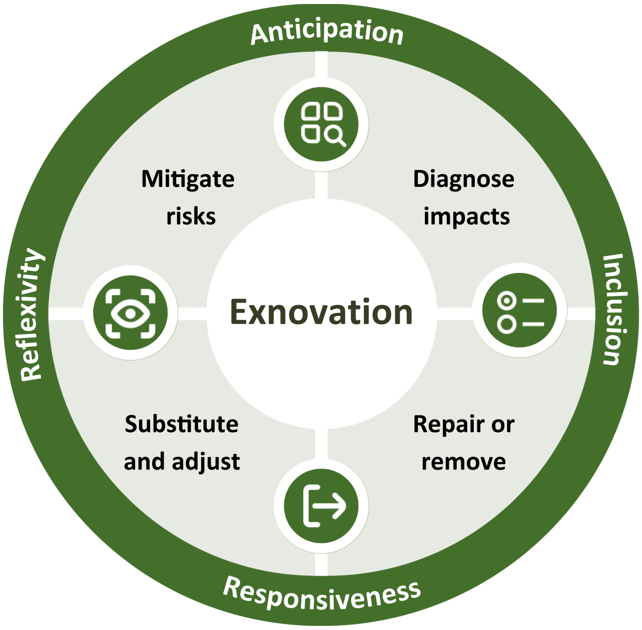


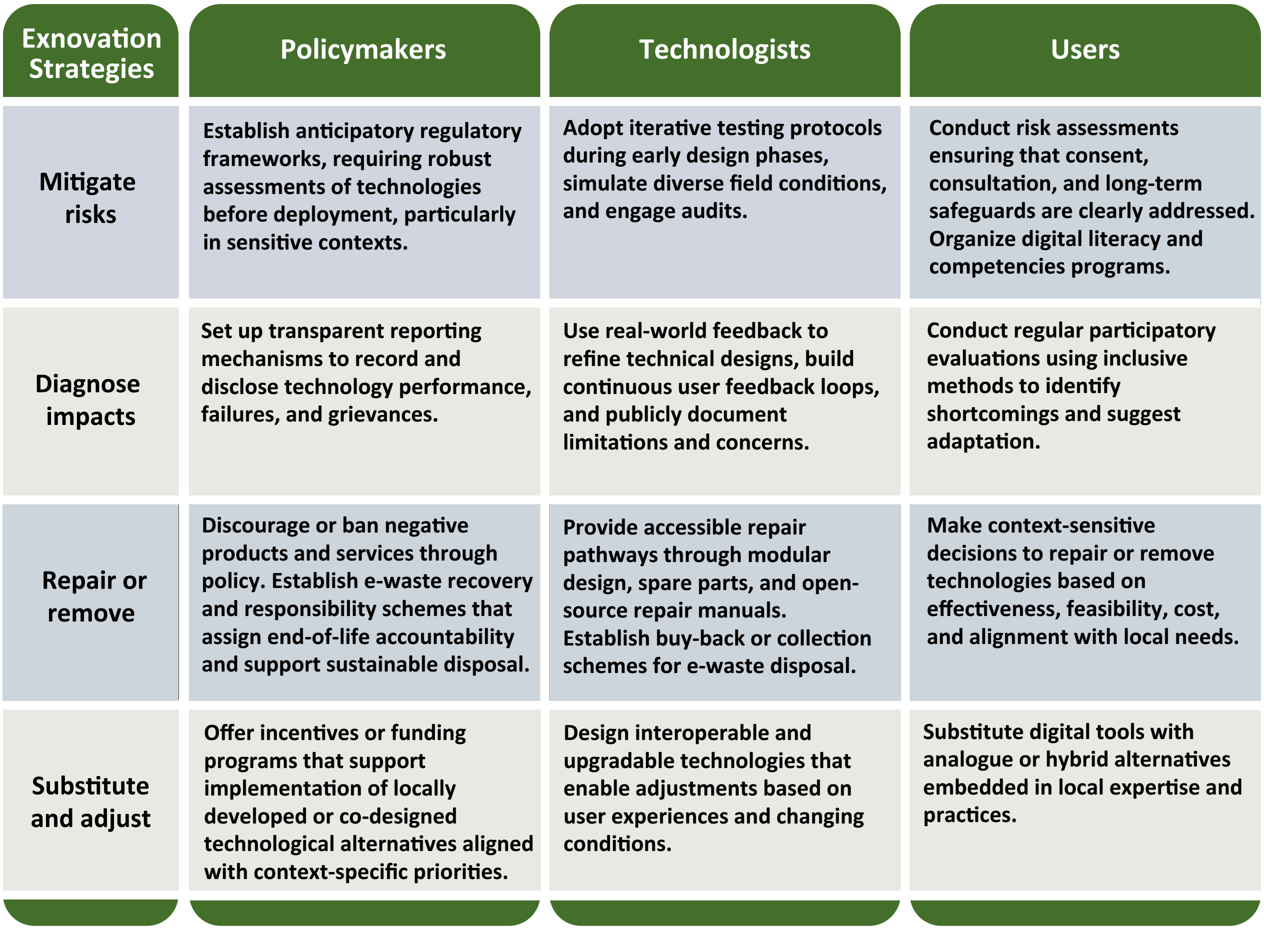
FIGURE 1 Exnovation strategies (inner circle) for conservation science and practice highlighting technological risk mitigation, impact diagnosis, repair or removal of concerns, and substitution or adjustment of changes, all linked to the principles of responsible innovation (outer circle).

Exnovation interventions do not begin with the removal of technological failures, but rather with critical evaluations of how technologies are designed, developed, and adopted, considering whose expertise is valued, for what purposes, and with what consequences (Holbek & Knudsen, 2020). In practice, exnovation involves a series of interventions across the entire lifecycle of technology design, implementation, and use, as well as their varied effects (Hartley & Knell, 2022). These complex interventions often involve challenging decisions that demand commitments to changing behaviors, attitudes, practices, or norms (David, 2018). Although responsible innovation often focuses on user responsibility, transformative interventions require shared accountability among stakeholders, including the shaping of institutions and technological design and development practices. Exnovation efforts can help clarify, negotiate, and mediate roles and power dynamics between policymakers, technologists, and users, recognizing their distinct contributions (Nelson et al., 2023). Figure 2 presents examples of potential exnovation interventions in conservation science and practice, acknowledging that specific stakeholder roles vary depending on context and local realities. When rights and responsibilities are carefully acknowledged and negotiated, exnovation strategies can support specific context-sensitive conservation efforts as described in the following sub-sections and illustrated by some examples.

2.1 | Mitigate risks

As technologies are increasingly applied across complex conservation sites, a wide range of impacts or unintended consequences may emerge (Barnhill-Dilling & Delborne, 2021). These uncertain and ambiguous aspects of technological development require anticipatory assessments and the design of mitigation plans that incorporate societal considerations and citizen participation (Jasanoff, 2003). Exnovation strategies play a crucial role in anticipating potential impacts through the identification of how technologies are designed, deployed, and used, by whom, in which contexts, and for what purposes. Through informal or formal institutions, these foresight practices can create robust planning that not only draws on technological expertise but also incorporates the concerns and insights of different stakeholders who are directly or indirectly affected by these technologies (Reichhardt, 2021).

In practical terms, risk mitigation measures rely on codes of conduct and regulatory frameworks that establish guidelines, standards, and safeguards for responsible technological development and use (Burri, 2023; November, 2018; Theodorou & Dignum, 2020). From governments to corporate responsibility, diverse initiatives establish technological risk procedures to mitigate the potential harms and unintended consequences associated with emerging technologies (Erman & Furendal, 2024; Srikumar et al., 2022). For instance, the European Union is responsible for one exemplary case of adopting the first-ever legal framework on AI technologies (European Commission, 2024a). This leading regulation assists in identifying risks created by AI applications, determining a list of high-risk applications, and prohibiting those that pose unacceptable risks. From a user-centered perspective, mitigation involves conducting risk assessments alongside best research practices that uphold consent, consultation, and ethical safeguards. Before deploying technologies, conservation practitioners can, for example, disclose the potential impacts of digital technologies as part of human research ethics, data collection agreements, and permissions respecting local socio-cultural norms. Strengthening digital literacy among users and affected communities is also essential to enhance local responses and build adaptive capabilities (Tinmaz et al., 2022). Such multi-layered mitigation procedures are critical in conservation settings, where the proactive identification of risks requires engagement with different stakeholders to prevent harms to vulnerable ecosystems and groups (Burgiel et al., 2021).



Exnovation Strategies	Policymakers	Technologists	Users
Mitigate risks	Establish anticipatory regulatory frameworks, requiring robust assessments of technologies before deployment, particularly in sensitive contexts.	Adopt iterative testing protocols during early design phases, simulate diverse field conditions, and engage audits.	Conduct risk assessments ensuring that consent, consultation, and long-term safeguards are clearly addressed. Organize digital literacy and competencies programs.
Diagnose impacts	Set up transparent reporting mechanisms to record and disclose technology performance, failures, and grievances.	Use real-world feedback to refine technical designs, build continuous user feedback loops, and publicly document limitations and concerns.	Conduct regular participatory evaluations using inclusive methods to identify shortcomings and suggest adaptation.
Repair or remove	Discourage or ban negative products and services through policy. Establish e-waste recovery and responsibility schemes that assign end-of-life accountability and support sustainable disposal.	Provide accessible repair pathways through modular design, spare parts, and open-source repair manuals. Establish buy-back or collection schemes for e-waste disposal.	Make context-sensitive decisions to repair or remove technologies based on effectiveness, feasibility, cost, and alignment with local needs.
Substitute and adjust	Offer incentives or funding programs that support implementation of locally developed or co-designed technological alternatives aligned with context-specific priorities.	Design interoperable and upgradable technologies that enable adjustments based on user experiences and changing conditions.	Substitute digital tools with analogue or hybrid alternatives embedded in local expertise and practices.

FIGURE 2 Examples of potential exnovation interventions applied to conservation science and practice, detailing potential contributions from policymakers, technologists, and users.

2.2 | Diagnose impacts

Assessments and ongoing user feedback are essential for evaluating how the deployment of digital technologies affects different environments and communities (Arts et al., 2015; Simlai & Sandbrook, 2021). On-site evaluations examine operational performances, disruptions to routine use, and misalignments with local activities, values, and socio-cultural norms (Sauls et al., 2023). A core component of this diagnostic work involves identifying how, when, and why technologies create concerns, limitations, or failures, ensuring that relevant shortcomings are recognized and addressed. In this process, users can document and register technological experiences through a range of qualitative and quantitative methods to assess the social, technical, and contextual dimensions of technology deployment. Research-oriented approaches include stakeholder surveys (e.g., White et al., 2021), semi-structured interviews (e.g., Brown et al., 2017), workshops (e.g., Jackman et al., 2023; Longdon, 2023), and digital ethnography (e.g., Pink et al., 2022). These methodologies help uncover user experiences, behavioral patterns, and socio-material entanglements that shape how technologies perform in practice, highlighting how contextual factors influence their functionality and applicability. Other practice-oriented methods for conservation projects include creating community advisory panels or local committees (e.g., Macdonald et al., 2021), prototyping participatory digital tools (e.g., Westerlaken et al., 2022), or running pilot programs and trial periods (e.g., Buddhipala & Nugi, 2024; Paneque-Gálvez et al., 2016).

Complementing these local diagnoses efforts, reporting mechanisms are essential for documenting and registering technological experiences from specific sites and linking them to broader decision-making and learning environments. Digital platforms can facilitate this process by promoting the documentation of field-based experiences and identifying what, how, and where interventions are needed. A notable example is the Inventory[1] platform, developed by the WildLabs network, which allows users to share practical reviews and updates on technical information. By enabling peer-to-peer knowledge exchange, such platforms support the collective documentation and evaluation of conservation technologies based on usability, functionality, and suitability for different contexts and needs (Urzedo et al., 2023). Online communities, such as the Conservation Technology Working Group (ConsTech WG),[2] further enable cross-sectoral dialogue to offer practical guidance for technological applications. Policymakers can play a critical role in institutionalizing these reporting platforms as a mechanism to register and respond to technological impacts. By doing so, reporting mechanisms help ensure that user experiences are not lost or overlooked but instead contribute to systematic feedback loops where industry actors and regulatory authorities are made aware of on-the-ground impacts and can respond through targeted interventions. The documentation and diffusion of these experiences, in turn, can enable technologists to incorporate feedback into design refinement processes, ensuring that technologies meet specific user needs and goals.

2.3 | Repair or remove technologies

Open-source and community-led software platforms are driving significant adaptations and transformations to improve the applicability of conservation technologies across different contexts (Lahoz-Monfort & Magrath, 2021). In contrast, hardware technologies, including drones and camera traps, often present more complex challenges related to field-based testing, durability, and adaptation to varied environmental and operational conditions (Aucone et al., 2023; Rowcliffe, 2017). As a result, these devices are often prone to damage, glitches, or malfunction when exposed to the harsh and unpredictable weather conditions commonly encountered in conservation settings. Rather than simply replacing faulty devices with newer models, repair practices offer a valuable intervention to extend the lifespan of technologies, reduce environmental impacts, and support users to participate in technological decision-making (Lloveras et al., 2024). Strengthening local repair capability requires access to spare parts, diagnostic tools, and open technical documentation (Hernandez et al., 2020). This necessitates intentionally designed technologies that are easy to repair and accompanied by open-access manuals and schematics, enabling users to perform basic maintenance and troubleshooting independently (Berger-Tal & Lahoz-Monfort, 2018). For example, the European Union's right-to-repair directive mandates manufacturers to provide access to spare parts and repair information through open, consumer-friendly platforms, promoting transparency and ease of maintenance for a wide range of products (European Commission, 2024b). These repair possibilities require the role of technologists in enabling the design of modular products and facilitating accessible repair pathways. Additional interventions also include several grassroots initiatives that foster locally led innovation and repair capabilities, such as the Earth Defenders Toolkit[3] and AIDESEP's Center for Territorial Information and Planning (CIPTA) in Peru.[4]

When repair is not viable, proper handling and disposal of digital devices become essential to avoid contaminations in ecologically sensitive conservation areas (Huang et al., 2014). In handling removal interventions, government initiatives can establish end-of-life recovery schemes and assign responsibility for safe disposal, particularly in remote or high-biodiversity regions (Wagner, 2013). These schemes may involve producer take-back processes or shared accountability models involving manufacturers, retailers, and users across the product lifecycle (Pickren, 2014). Addressing these responsibilities is crucial not only to preventing the accumulation of electronic waste in ecosystems but also for ensuring appropriate pathways for recycling, reuse, or secure disposal. While these interventions focus on hardware management, removal strategies can operate at the policy level. In this broader sense, removal includes the deliberate phasing out of harmful practices or materials through regulatory mechanisms, such as removing environmentally damaging subsidies or restricting hazardous substances (e.g., Rinscheid et al., 2022). This expanded view highlights that removal is not only about managing physical waste, but also about dismantling systemic drivers of harms.

2.4 | Substitute and adjust changes

The removal of technological issues can disrupt existing conservation activities, necessitating strategies to substitute and adjust changes (Hartley & Knell, 2022). Through these transitions, exnovation strategies can support the replacement of devices, systems, or practices with simpler or locally driven solutions (Maldonado-Mariscal & Hölsgens, 2024). Rather than relying solely on high-tech or advanced solutions to address previous problems, substitution creates space for place-based innovation that draws on diverse alternatives. Potential substitutions include low-tech devices, community-led tools, creative non-technological interventions, and adaptations of existing infrastructure that leverage local expertise. For instance, conservation do-it-yourself (DIY) groups enable not only the adoption of low-tech solutions but also the innovation of approaches tailored to specific place conditions (Lahoz-Monfort & Magrath, 2021). These grounded innovations are influential in conservation monitoring, where high-tech methods are replaced with simpler technologies and local capabilities, such as open-source bioacoustic sensors (Whytock & Christie, 2017) and low-cost drone designs (e.g., Mesquita et al., 2021). Successful DIY drone design and implementation by different Indigenous groups further demonstrate the potential of substituting high-tech products in environmental monitoring efforts (Paneque-Gálvez et al., 2017). These interventions highlight that technological advancement alone is insufficient to address conservation challenges; they must also embrace diverse capabilities and appropriate institutions aligned with socio-cultural contexts (Urzedo et al., 2025). When these substitutions occur, continuous monitoring should track the effects of these changes and support ongoing adaptation. This ensures that new practices are refined over time and remain responsive to place-based needs and goals (Fuchs & Ziegler, 2024).

3 | MOVING FORWARD

As technologies continue to shape complex conservation settings, responsible innovation requires careful attention to the impacts, limitations, and failures of digital practices. From an exnovation perspective, the key challenge is not merely the development of new advanced technological tools, but the mitigation, phasing out, or replacement of existing practices that reinforce harmful, extractive, or exclusionary dynamics. In this paper, we propose exnovation strategies as a critical complement to innovation in conservation activities. These strategies offer pathways for negotiating responsibilities across diverse stakeholders and guiding context-sensitive technological design and deployment. Effective implementation depends on the expansion of collaborations and practical procedures based on further research evidence to identify and mediate the distinct and complementary roles and power imbalances between policymakers, technologists, and users in specific settings throughout the innovation cycle.

Despite these challenges, exnovation can offer a suite of tangible actions that can enhance inclusivity and participatory conservation technologies. Promising interventions include the development of technologies with repairability and modularity to enhance adaptability and consider local capacities. We also emphasized the value of grassroots and DIY initiatives that promote low-tech and community-led innovations, reflecting local knowledge and leadership. To ensure accountability and ethical practices, regulations and formal agreements are also essential to oversee technology removal and restrict harmful tools or services. Ultimately, by fostering collaboration across sectors and redistributing responsibility, exnovation can realign technological design and use with transformative goals in conservation efforts.

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The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All information discussed in this article is drawn from previously published sources. No new data were generated or analysed.

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ENDNOTES

[1] The Inventory platform: https://wildlabs.net/inventory.

[2] The Conservation Technology Working Group: https://conbio.org/groups/working-groups/conservation-technology-working-group.

[3] The Earth Defenders Toolkit: https://www.earthdefenderstoolkit.com/home/.

[4] AIDESEP's Center for Territorial Information and Planning: http://cipta.ddns.net/.

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