The Environment-Vulnerability-Decision-Technology Framework: A Process for Developing Multi-Disciplinary Decision Support Systems for Sustainable Development Applications

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The Environment-Vulnerability-Decision-Technology (EVDT) Framework is a process for developing multi-disciplinary, interactive decision support systems (DSS) for a variety of sustainable development applications. This framework seeks to support the use of Earth Observation and socioeconomic data in a format usable by non-experts, while harnessing cloud computing, machine learning, economic analysis, complex systems modeling, and systems engineering. It is characterized by five basic elements: (1) the use of systems architecture & stakeholder analysis to identify needs and understand the context; (2) collaborative development of the DSS that continues stakeholder engagement past the initial systems architecting; (3) a concept of the sustainable development application as a complex socio-enviro-technical system, typically involving the Environment, Human Vulnerability and Societal Impact, Human Behavior and Decision-Making, and Technology Design; (4) an interactive decision-support system; and (5) A consideration towards modularity and re-use of DSS components in future applications.

In particular, the EVDT Framework draws from the fields of systems architecture (and other systems engineering techniques), GIS, collaborative planning, and remote observation, each of which have complementary aspects that can be brought to bear on development challenges, particularly those of relatively small spatial scales (municipalities to metropolitan regions) that tend to be underserved by major international development programs. Over the past few years, the EVDT Framework has been used to develop DSSs for mangrove conservation in Brazil, flood resilience in Indonesia, invasive plant species management in Benin, cranberry bog renovation and wetland restoration in Massachusetts, and COVID-19 response in six major metropolitan areas around the world. These projects involved both space and non-space stakeholders including the Instituto Pereira Passos (IPP) (Rio de Janeiro's municipal data agency), GGPEN (the Angolan space agency), MICITEC (Chile's science ministry), the Universitas Diponegoro of Indonesia, and the Yurok tribe of modern day California, among others. Through these applications and collaborations, the EVDT framework has developed from a conceptual framing to a concrete process that is shown to be repeatable across geographic contexts.

This paper presents the details of the framework, including (1) a discussion of the motivation for the creation of this framework, including its benefits, limitations, and methodological underpinnings; (2) a step-by-step guide for applying the framework applications, including a discussion of different potential use-cases; (3) examples of applications (such as those mentioned previously), including lessons learned from each; and (4) areas of ongoing improvement, including improved modularity and re-use.

Keywords: earth observation, systems engineering, decision support, sustainable development, modeling

Acronyms/Abbreviations

CATWOE	Customers, Actors, Transformation process, Worldview, Owners, and Environmental constraints
DSS	decision support system
EO	earth observation
EOS	earth observation system
EVDT	Environment-Vulnerability-Decision-Technology
GEO	Group on Earth Observations
GIS	geographic information systems
IPP	Instituto Pereira Passos
LIDAR	light detection and ranging
NGO	non-governmental organization
PGIS	Participatory GIS
PPGIS	Public Participation GIS
RFF	Resources for the Future
SAF	Systems Architecture Framework
SDG	Sustainable Development Goal
SES	socio-environmental system
SETS	socio-environmental-technical system
SPADE	Stakeholders, Problem, Alternatives, Decision-making, Evaluation
SSM	soft systems methodology
UN	United Nations
US	United States
VALUABLES	Valuation of Applications Benefits Linked with Earth Science

1. Background

Over the past few decades, historical means and theories of economic development (particularly the extensive use of fossil fuels) have been deemed insufficient due in large part to humanity reaching and exceeding certain planetary boundaries or capacity limits, including those of climate change, biodiversity loss, ocean acidification, and the nitrogen cycle [1]. This recognition led to the rise of sustainable development: the concerted pursuit of three related (sometimes aligned, sometimes opposed) objectives: economic development, social development and environmental protection [2–4]. This rise can been seen in the engineering literature, where sustainability is the fastest growing of the 'ilities' [5], as well as more broadly in the adoption of the United Nations (UN) Sustainable Development Goals (SDGs) [6].

Due to the interdisciplinary nature of sustainable development, numerous fields and perspectives have sought to contribute to its pursuit. Among these are earth observation (EO), geographic information systems (GIS), systems engineering. EO can provide data on the environment and human landscape with spatial and temporal coverage that is infeasible via in-situ data collection methods, as well as a certain global perspective and context. The Group on Earth Observations (GEO) has published a report detailing how EO is critical to the pursuit of the SDGs [7]. The Valuation of Applications Benefits Linked with Earth Science (VALUABLES) consortium, formed by a partnership of Resources for the Future (RFF) and NASA, is working to assess the societal benefit of various earth observation systems (EOSs) in specific case studies [8, 9]. And the NASA Applied Sciences Program within the Earth Science Division has been working to expand its sustainable development activities for more than a decade now [10, 11].

The GIS field, meanwhile, "allows geographers to integrate diverse types of data over different spatial scales from the regional to the global, while the advanced capabilities of GIS for organizing and displaying these data transform the geographer's view of the world" ([12] as paraphrased in [13]). It originated in the 1960s and 70s with experimental efforts of the Canada Geographic Information System and the US Bureau of the Census to digitize their demographic and land cover data [14]. Its use rapidly expanded in the subsequent decades, with governments use maps to visualize their jurisdictions and motivate action, as Chicago has done by visualizing food deserts and mapping where new supermarkets are both needed and economically viable [15]. Since the turn of the millennium, spatial data has become deeply ingrained economics, urban studies, private industry, social networks, environmental science, public health, criminal justice, and more [16].

Systems engineering, a field historically tied to military, aerospace, and industry, is "an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem" [17]. It thus has some potential utility for the highly interdisciplinary sustainable development domain. Recent years have seen promising efforts made in this vein. A recent special issue of *Sustainability* [18] was dedicated to systems engineering, demonstrating the variety of tools and techniques that systems engineering can bring to bear on sustainable development. For example, in 2020, Honoré-Livermore et al. sought to address the SDGs in arctic coastal regions via an approach grounded in socio-environmental systems (SESs) and the Stakeholders, Problem, Alternatives, Decision-making, Evaluation (SPADE) methodology [19]. The SPADE methodology was developed specifically for sustainable development applications. The five components of its name constitute five non-linear steps, each of which has various specific associated methodologies: **S:** Stakeholders, **P:** Problem, **A:** Alternatives, **D:** Decision-Making, and **E:** Evaluation [20]. Van Zyl and Root meanwhile used a transdisciplinary approach involving Wilbur's integral systems theory [21] and the Customers, Actors, Transformation process, Worldview, Owners, and Environmental constraints (CATWOE) framework from soft systems methodology (SSM) [22] to design sustainable agricultural principles in New Zealand [23].

It should be noted that this is not the first time these fields have sought to involve themselves in the development and planning domains. In the United States (US) during the 1960s and 70s, researchers and practitioners made efforts to apply both EO and systems engineering to urban and regional planning. These attempts were largely unsuccessful and, in some cases, actively harmful, in many cases owing to a lack of consideration for how these projects would impact the numerous different stakeholders involved. A history of some of these efforts (particularly systems engineering and EO) is available in Jennifer Light's book *From Warfare to Welfare* [24], and some of the authors of this paper recently conducted a review of the systems engineering literature during this period [25]. Such difficulties prompted self-critique within these fields and the development of new methodologies and best practices. In systems engineering, it led to the rise of SSM and a massively expanded emphasis on stakeholder analysis [26, 27] and systems architecture [28, 29]. In EO, it has prompted the much more recent rise of critical remote observation, which similarly seeks to directly engage and empower a variety of stakeholders, in addition to targeting applications likely to improve socioeconomic and environmental injustices [30].

GIS has perhaps the most robust literature of self-critique of these three fields. Similarly to the closely related field of EO, many early GIS applications were technology-driven rather than need-driven. This led to powerful critiques by Pickles and others [31] which in turn resulted in a reconsideration of the top-down nature of the field and the identification of several potent reasons for broadening the base of participation. First, there was the recognition that the developer of a GIS is not the supreme authority on all fields. "It is the geomorphologist who is best able to choose the data model for representation of terrain in a GIS, not the computer scientist or the statistician, and it is the urban geographer who is best able to advice on how to represent the many facets of the urban environment in a GIS designed for urban planning" [14]. Second, there was a recognition of the equity concerns. Users and disadvantaged communities needed to be involved in the development of GIS data, analysis, and use if they were going to have a meaningful chance of improving their circumstances [32]. The Canadian International Development Research Centre noted that, "It is impossible to have sustainable and equitable development without free access to reliable and accurate information" [33]. Motivated by this reasoning, since the early 2000s several subfields have developed, all aimed at deconstructing current practices and expanding participation. These include Bottoms Up GIS [32], critical cartography [34, 35], GIS and Society [36], and Public Participation GIS (PPGIS). The last of these, which sought to directly involve the public, would become the most widely used, and would be associated with the broader field of Participatory GIS (PGIS) [36], which also included other stakeholders, including government officials, non-governmental organizations (NGOs), private corporations, etc. It should be noted that these fields seek involvement in both the production of data and in its application, not merely one or the other [32, 37]. More recently these lesson from GIS have been incorporated with similar lessons from other data science and design fields to form methodologies and approaches such as Data Action [38], Data Feminism [39], and Design Justice [40].

All three of these fields (EO, systems engineering, and GIS) share a history of practically and ethically troubled development applications followed by a more recent trend towards diverse stakeholder involvement and participation. All three are increasingly being used for sustainable development applications, often independent of one another but sometimes in ad hoc combinations. A framework that integrates these three and builds upon the critical lessons learned by each could propel sustainable development applications forward. This paper will present such a framework, including a guide for its application while drawing on a collection of case study applications. It will conclude with discussion of areas of ongoing improvement.

2. EVDT Framework

The Environment-Vulnerability-Decision-Technology (EVDT) Framework is a process for supporting sustainable development decision-making [41] characterized by five elements:

1) The use of systems architecture & stakeholder analysis to identify needs, design the decision support system (DSS), and understand the context through the use of the Systems Architecture Framework (SAF). This requires significant engagement with as many of the stakeholders as is feasible (if not more).
2) Collaborative development of the DSS that continues that stakeholder engagement.
3) A concept of the sustainable development application as a complex socio-environmental-technical system (SETS), typically involving the Environment, Human Vulnerability and Societal Impact, Human Behavior and Decision-Making, and Technology Design. This concept undergirds the DSS architecture and is critical as it provides the capability both

for detailed technical analysis as well as feeding back into the design of data collection systems .

4) An interactive DSS. This can take the form of an in-browser page, a standalone application for a computer or phone, or even a tabletop exercise with paper documents.
5) A consideration towards modularity and re-use in future applications. This includes both technical components of the DSS product and broader capacity building in the community.

Each of these elements span the entire lifecycle of an EVDT project, but can still be usefully considered in the order listed. The next several subsections provide more detail on each of these five elements, but first, several example EVDT projects will be introduced as they will be used to illustrate the five elements. The contexts, stakeholders, and system objectives, forms, and functions for each of the case studies are summarized in Table 1 of Appendix A. The specific methodologies that they use for each of the five EVDT Framework elements are summarized in Table 2 of Appendix A.

2.1. Case Study Projects

Massachusetts Cranberry Farming and Bog Restoration: This project, led by Jaffe [42, 43], seeks to support land-use decision-making by cranberry farmers in Massachusetts, along with ecologists, government officials and others. In particular, she is seeking to provide information around the ecosystem services and ecological benefits provided by bog restoration (as opposed to continued farming or development), so as to support future land use decisions. The project was motivated by a long term collaboration between the MIT Media Lab and hte Living Observatory, a public interest learning collaborative centered around the Tidmarsh Cranberry Farms Restoration Project [44].

Fig. 1 Left: Operational Cranberry Farm (Glorianna Davenport) Right: Cranberry Farm Post Restoration (Kirsten Foresto). Figure from [43]

Pekalongan Coastal Flooding and Subsidence: This project, led by Lombardo [45], seeks to support local leaders in Peklongan City, Indonesia to make resilience and mitigation decisions in the face of coastal flooding and land subsidence. Potential options include sea walls, mangrove replanting, and development of a flooding early warning system, among others. The project was an extension of an ongoing partnership for the Vida COVID-19 response project, which was previously presented at IAC [46].

Fig. 2 Left: Flooding in Indonesia. Right: An existing sea wall (yellow) and mangrove grove (green) in Pekalongan. Figure adapted from [45]

Invasive Plant Management on Lake Nokoué: This project, led by Ovienmhada [47, 48], seeks to support a local enterprise in the management of water hyacinth, an invasive aquatic plant species, that blocks waterways and has numerous adverse environmental, economic, and health effects in and around Lake Nokoué, Benin. Activities include detecting and tracking the growth of water hyacinth and targeting removal of the plant in the most impactful areas. This project originated out of an invitation for collaboration from Green Keeper Africa, a local social enterprise organization.

Fig. 3 Left: A stand of water hyacinth on Lake Nokoué. Right: Water hyacinth encroaching on an acadja fishing pond. Figure adapted from [48]

2.2. Systems Architecture & Stakeholder Analysis

The first element of the EVDT Framework builds upon Maier's [28] and Crawley's [49] work to apply systems architecture to international collaborations [50] and sustainable development [48]. This takes the form of the SAF, pictured in Figure 4. This framework seeks to center the full network of stakeholders and invite them into a collaborative development process. By stakeholders, we mean the people, organizations, and communities that either influence the design and operation of the system or are impacted by the system.

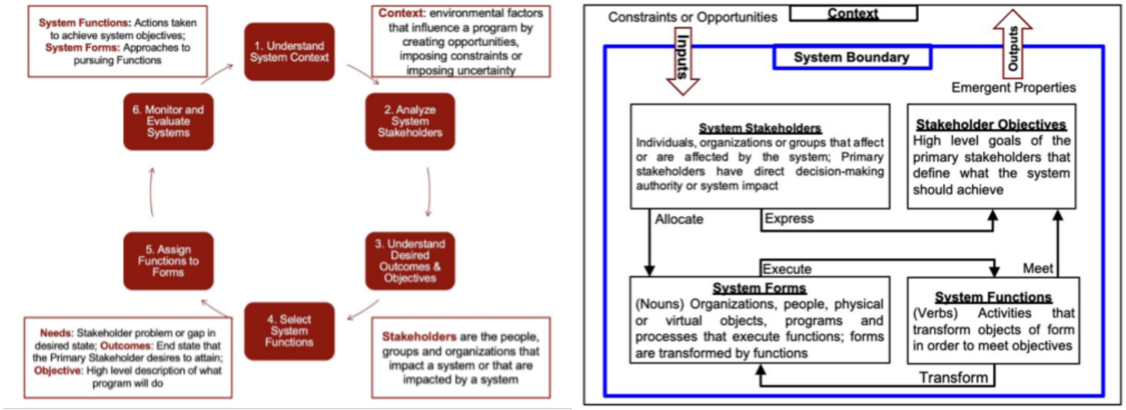

Fig. 4 Left: Six steps of SAF. Right: Components of the system as envisioned by SAF

The stakeholders are involved in defining the system, understanding the System Context (the external factors that influence and constrain the system), identify System Objectives (the high level description of what the program will do), and develop the System Functions (the specific actions taken to achieve the objectives) and System Forms (the approaches and structures used to pursue the functions).

Notably unlike some forms of stakeholder analysis that primarily use stakeholder input to inform system requirements at the beginning of the development cycle, SAF seeks to involve the stakeholders in ongoing monitoring, evaluation, and participation. Multiple techniques are available for coordinating input and involvement from various stakeholders, with varying levels of detail, time requirements, and balance of quantitative versus qualitative information. Examples include multi-stakeholder tradespace exploration [51], multicriteria negotiations [52], and collaborative sketch planning [53].

All of the case studies relied heavily upon qualitative interviews with a variety of stakeholders, not just the direct local point-of-contact, as well as in-person site visits for direct observation whenever possible. Jaffe interviewed multiple cranberry farmers, ecologists and environmental activists at several different organizations, multiple academics, and both state and federal government officials. She then organized the stakeholders into a relational map, shown in Figure 5, that both provides improved understanding of the overall structure of stakeholder relationships and can be used for stakeholder value network analysis [27].

Ovienmhada, meanwhile, classified the Lake Nokoué stakeholders as primary (those that make direct decisions about the design of the water hyacinth management system), secondary (that that have influence on the primary stakeholders), and tertiary (those who exert little control over the system but are impacted by it); before linking these stakeholders to particular functions performed by the existing water hyacinth management system and their objectives for an improved system, as shown in Figure 6.

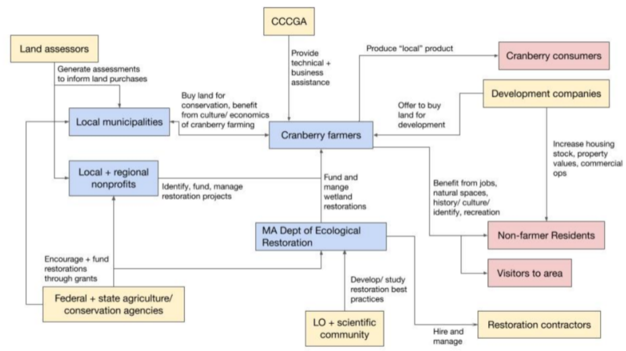

Fig. 5 Stakeholder map of the MA Cranberry Industry. Figure from [43]

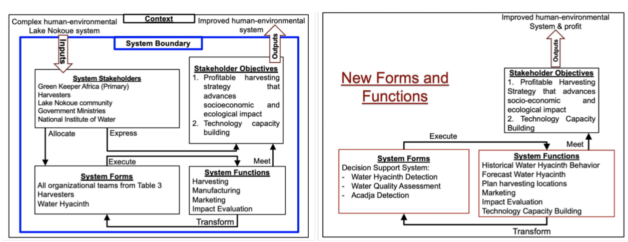

Fig. 6 Left: Summary of the existing system architecture for water hyacinth management from the perspective of Green Keeper Africa. Right: Summary of the proposed forms which will execute functions that meet stakeholder system objectives. Figure adapted from [48]

Lombardo, meanwhile, did not classify or map stakeholders (though he promises to do so in the future) [45]. He did conduct interviews with local academics, local government officials, and representatives of three different NGOs which were used to identify the Needs and Desired Outcomes for each stakeholder, before synthesizing these into two System Objectives to guide the development of the DSS.

These show that the exact form of initial of identifying and engaging stakeholders can vary, but it must be more involved than directly copying down the stated objectives of a singular point-of-contact. When applying EVDT, the types of stakeholders not directly contacted be identified and the reasons why they have not been contacted carefully considered. It is worth remembering that "the 'suspicious moonshiners in Appalachia' who 'took a few rifle shots' at aerial mappers did so not because the intentions of the mappers were 'not always understood,' but because those intentions, and the powerful forces being them, were understood only too well." [54].

2.3. Collaborative Development

Involving stakeholders in the development process, in addition to the requirements definition process, is key for ensuring adoption and capacity building. This has been recognized by the PGIS movement, which increasingly emphasizes the importance of open source software [55, 56]. It is also core to the Data Action framework which, responding to the idea that "data is never raw, it's collected," emphasizes the use of participatory and collaborative methods for collecting and using data [38]. Collaborative development is increasingly feasible as barriers have dropped over the past couple of decades. Knowledge and familiarity with computers and programs has expanded, access to sufficient hardware is increasingly common (particularly with the rise of cloud computing platforms), and both synchronous and asynchronous online collaboration tools have proliferated. Obviously such barriers have not been universally eliminated. Furthermore, even in the absence of barriers, not everyone desires to be a computer programmer, earth scientist, EO specialist, or social scientist, even part-time. Collaborative development must therefore take different forms in each project, being as welcome as possible to all while accommodating stakeholder preferences and constraints.

Lombardo hosts near weekly virtual meetings with multiple Indonesian stakeholders to provide updates and solicit feedback. Experimental roleplaying scenarios are currently being conducted with Indonesian stakeholders that will assess user satisfaction, desire to adopt, and other metrics that can be used to improve future iterations of the DSS. Jaffe hosted the cranberry bog DSS online, made the source code publicly accessible during development, published an instructional video, and has solicited feedback from users [43]. Even though the current version of the DSS is viewed as "an important starting point for allowing stakeholders to interact with and become familiar with the potential benefits of ecosystem services," the feedback already received led to the identification of several concrete areas of improvement and future development. Ovienmhada has supplemented periodic virtual meetings with multiple extended in-person trips to Benin, including the Lake Nokoué area. These visits enabled much more direct involvement from stakeholders and a more rapid feedback cycle, such as directly trialing the on-site construction and deployment of water sensors for monitoring water hycacinth growth conditions.

Something notably missing across these cases is the direct involvement of local stakeholders in the programming of DSSs and other forms of analysis. While learning and capacity building of other forms has certainly occurred, this represents an area for improvement.

2.4. EVDT Questions

The EVDT Framework conceptualizes the application system from two different perspectives. The first is the system boundaries and stakeholders perspective from SAF shown in Figure 4. The second perspective focuses on combining the established fields of sociotechnical systems [57–59] and socio-environmental systems [60] into SETS. To accomplish this, at least four components are considered: the Environment (data including Landsat, Sentinel, VIIRs, in-situ environmental data and knowledge, etc.); Human Vulnerability and Societal Impact (data including census and survey-based demographic data, eocsystem services valuations, NASA's Socioeconomic Data and Applications Center, local knowledge of impacts, etc.); Human Behavior and Decision-Making (data including policy histories, mobility data, urban nightlight data, community input, etc.); and Technology Design for earth observation systems including satellites, airborne platforms and in-situ sensors (data including design parameter vectors for such systems). The data from each of these domains is used by established models in each domain, which are adapted to work in concert to address the needs identified during the stakeholder analysis. These four components, shown in Figure 7, seek to encapsulate the major interacting aspects of sustainable development and consider them from a SETS perspective.

We are far from the first to argue that such integration is necessary, nor to recognize that it is easier said than done. The closest attempt to what is proposed here is probably that of Shahumyan and Moeckel, though their approach focused on linking together existing models in a loose manner using ArcGIS Model Builder, to avoid having to gain access to proprietary source code. While their example focused on combining transportation, land use, mobile emissions, building emissions, and land cover, with only limited feedbacks, their approach could be extended to capture the full feedback loops proposed by EVDT. Their example is also proof that the kind of loose integration of library of models that EVDT envisions is possible [61].

The motivation for combining so many variables from different disciplines stems from both push and pull factors. The push factors are the simple increase in availability of data, along with the increase in the interoperability of the variables (which this work itself is trying to contribute to).

The primary pull factor is our increased understanding of - and appreciation for - the complex relationships between these domains, relationships that were previously ignored in analyses [62].

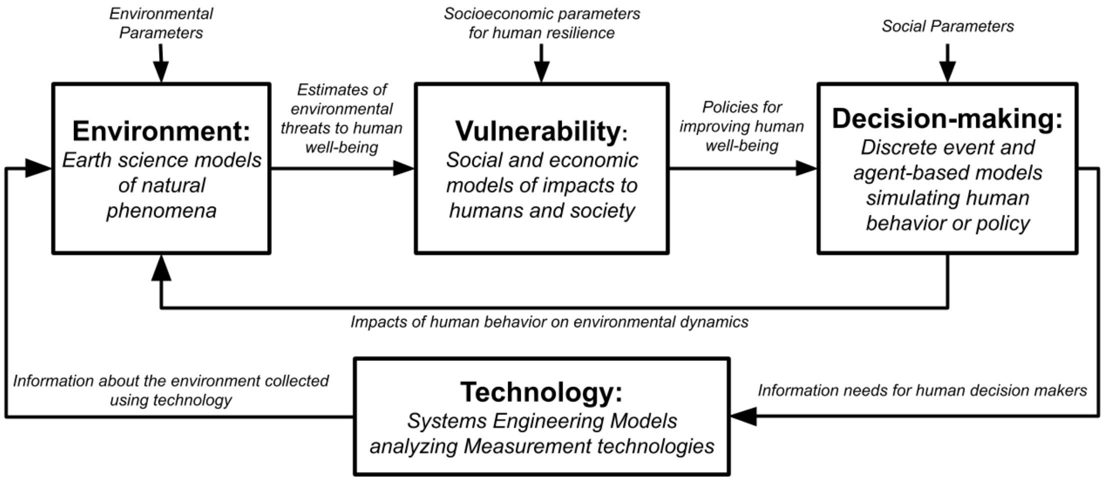

Fig. 7 Baseline version of the Environment - Vulnerability - Decision - Technology Model (Generic Case)

The set of four models with the particular linkages shown in Figure 7 are not the only form that EVDT can take, merely the most general arrangement. Some applications may involve replacing a model with a human-in-the-loop (e.g. having a user or community member substitute for the decision-making model) or omitting a model altogether. Jaffe used the former in the cranberry bog project (see Figure 9 in Appendix B). Various EO-derived data products (land-use-land-cover, topography, precipitation, etc.) constituted the Environment component, several InVEST models to simulate ecosystem services under different scenarios for the Vulnerability component, a human user operating the DSS for the Decision-making component, and an examination of various potential and current wetland restoration research programs for the Technology component.

For other applications, it may make sense to conceptually break a model into two or more components. In the Vida coronavirus response project (shown in Figure 11 of Appendix B and presented previously at IAC [46]), it was considered worthwhile to separate the social impact model into two components, one focusing on public health (the obvious priority when dealing with COVID-19) and one focusing on non-health metrics (such as income, employment, etc.). Such a separation can be useful if either significantly different modeling methodologies are going to be used or if the linkages with the other EVDT components are different from one another. One way to determine the optimal arrangement of EVDT components is to consider what questions the stakeholders are seeking to answer with an application of EVDT. For instance, the default EVDT arrangement shown in Figure 7 was motivated primarily by the following four questions:

1) What is happening in the natural environment?
2) How will humans be impacted by what is happening in the natural environment?
3) What decisions are humans making in response to environmental factors and why?
4) What technology system can be designed to provide high quality information that supports human decision making?

Alternate questions may result in a different configuration or set of components. The point of EVDT is not to insist upon a particular set of linkages and feedbacks, but rather to encourage a consideration of such linkages between domains in general, and to consider them through a systems engineering perspective. Of course answering the structuring questions, and even phrasing them in the first place, requires the involvement of stakeholders.

2.5. *Interactive Decision-Support System*

A key aspect of the term DSS is the word "support." Crawley et al. state that the goal of a DSS is to "*enhance* the efficiency of decision makers by providing tools to quantitatively and qualitatively explore a space of alternatives for single or multiple decisions" [emphasis added] [29]. This means that the EVDT-developed DSS should not present decisions as a *fait accompli* but instead support stakeholders in developing their own solutions. Ideally this means that individual stakeholders can directly handle and explore any simulations or models used, along with their underlying assumptions and structure. If this is not feasible, an indirect form of interaction can be used, such as when a stakeholder provides verbal instruction to someone who then implements that instruction in the DSS. The latter option can be quite useful when there are barriers of language, familiarity, or technical knowledge, and is commonly used in purposeful gaming [63], wargaming [64–66], and role playing gaming [67, 68]. Additionally, in contrast to Crawley's definition which centers on the "efficiency of decision-makers," we argue that an ideal DSS should cause a decision-maker to consider multiple perspectives (such as the four models of EVDT and those of other stakeholders) and thereby make *better* decisions as well.

As mentioned previously, Jaffe made the cranberry bog DSS directly available online. This DSS, shown in Figure 8, does not directly perform any computations, but it does present a range of scenarios (based on the relative proportion of bogs used for farming or restoration) and the outcomes of those scenarios on water quality, habitat quality, and carbon storage. Rather than preesnting a singular policy "solution", this DSS provides information in an easy-to-understand fashion so that decisions can be made about individual bogs or about the entire industry.

In the Pekalongan coastal resilience project, meanwhile, Lombardo is prototyping the ability for the user to propose new flood mitigation interventions (such as sea wall placement), which the DSS will then use to recalculate and present hazard and vulnerability indices for the city.

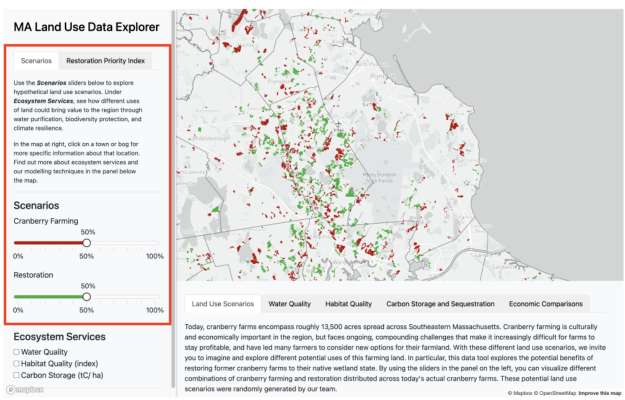

Fig. 8 Cranberry Bog Web Application DSS, highlighting the Land Use Scenarios Explorer. Figure from [43]

2.6. *Re-use & Community Development*

One of the key motivations of participatory, stakeholder-involved processes is capacity building. In the case of the EVDT Framework, this includes both capacity building in a specific application community and in the broader practitioner community of those using EO, GIS, and systems engineering for sustainable development. To that end, the DSS should be designed with re-use and modularity in mind. The ability to track mangrove health in Brazil [**?**] proved to be useful in a later application in Indonesia [45]. A key aspect of this is making as much of the DSS available in open source repositories (some of which are already available online [69–71]).

The second form of capacity building is pursued by developing a community of practice around EVDT and related endeavors. Currently we host publicly-accessible monthly meetings for active participants and interested parties to present on recent endeavors, share information, and identify common problems. In the future we plan on hosting more instructional and demonstration material online, such as Jaffe's instructional video for the cranberry bog DSS [72].

2.7. *Intended Applications and User Types*

The EVDT Framework was designed with a range of sustainable development applications in mind, with a particular focus on applications at the scale of an individual municipality or small province (as opposed to a global study or a examination of a particular neighborhood). Some potential applications include:

1) To inform sustainable development policies. Ex) Comparing the impact of different conservation and zoning policies on the local environment and on economic outcomes.
2) To educate on the connections between the different EVDT domains. Ex) Demonstrating the local ecosystem services value of treecover in an urban environment.
3) To facilitate the comparison of different remote sensing data products for particular applications. Ex) Considering whether to commission periodic aerial surveys of an area or to rely on "free" civil satellite data, such as Landsat and Sentinel.
4) To facilitate the exploration and evaluation of new sensing technology architectures for particular applications. Ex) Designing a new light detection and ranging (LIDAR) satellite to assist forest management in a particular region.
5) To facilitate scientific research on ecosystem services and/or the impacts of human behavior on the environment. Ex) Simulating different causal connections and comparing the simulated data with historical data, to assess the strength of those connections.
6) To provide a basis for studies of the effectiveness of different DSS attributes. Ex) Assessing visualization techniques, workshop formats, etc.

These applications are varying levels of interest and importance to different stakeholders, and some could potentially be viewed as competing for development resources and focus. In some cases they may rely upon different configurations of the EVDT components. For instance Items 3) and 4) require a functional model of the relationships between different remote observation design parameters and performance parameters, along with a means of visualizing and exploring the tradespace. A user who is predominantly interested in Item 1) may find this functionality irrelevant or outright distracting.

On the other hand, some applications are more complementary. While the Item 1) is likely to be a government official or community member while the Item 6) user is likely to be an academic researcher, the findings from Item 6) would result in the design of EVDT being improved, so as to better serve the needs of the Item 1) user.

Ideally, EVDT will be open to all these applications and more. In practice, care must be taken so that interests of one user group do not unintentionally dominate those of others or, worse, that the interests of the developers do not send them on a path counter to the interests of the users. This will thus require ongoing discussion within the EVDT community.

3. Ongoing Efforts

The EVDT Framework is well posed to leverage EO, systems engineering, and PGIS to tackle targeted sustainable development challenges. It is, however, still a new framework that is actively being built out and refined. In particular there are various threads of work that are still necessary to ensure success.

Develop a robust and reusable code base, backed up by a solid development pipeline. Many academic projects are experimental one-offs that have limited reusability, even within the same research group. While the initial EVDT projects sought to share code and techniques, there still was (and is) significant use of different platforms and methodologies that were not readily compatible. As these projects complete their initial development cycles, it is necessary to specify interoperability standards and put in place a concrete development pipeline. Several structures for these are currently being considered. Not only will these enable more ready reuse, but they will promote participation from outside the community of initial developers.

Expand participatory access We are cognizant that making EVDT truly participatory is easier said than done, but we do believe it is a worthy goal. In addition to interoperability standardization, the accessibility norms will need to be clarified as well, so as to ensure usability by individuals with a wide range of backgrounds. Existing prototypes have made some steps in this direction, such as by having multiple language options available. Thus far, this has been accomplished by existing language knowledge of code moderators as well as the occasional volunteer translator, but more targeted efforts may be required in the future to specifically recruit translators for specific languages. Language is not the only accessibility barrier, however. Terminology, presentation, and interactivity can also be differentially accessible to different individuals, depending on factors such as educational or cultural background. That said, these difficulties can be addressed via some of the same methods that are already core to the EVDT methodology: namely partnerships with local collaborators; stakeholder analysis; and iterative, participative design.

Conduct critical evaluations of the framework and projects, including retrospectives. In order to ensure that the EVDT Framework and its applications are actually advancing the goals of sustainable development, critical evaluations are key. Some of this is already being conducted, in the form of usability studies that inform both the design of a specific DSS and EVDT DSSs in general. As the corpus of EVDT projects is built out, however, retrospective studies, including ones occurring several years after the conclusion of a project, will be important for ensuring that the framework is both effective and not inflicting unintended harms (as has been common in many past technocratic interventions).

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Appendix A (Case Study Summaries)

Table 1 Summary of case studies contexts

	Massachusetts Cranberry Farming & Bog Restoration	Pekalongan Coastal Flooding & Subsidence	Invasive Plant Management on Lake Nokoué
Context	The MA cranberry industry is changing and decisions must be made regarding whether to maintain existing farms, develop land for other uses, or restore them to natural conditions.	Due to land subsidence, sea level rise, and increased frequencies of extreme weather, the risk of coastal flooding is increasing. Decisions must be made regarding mitigation, resilience, and adaptation.	The invasive water hyacinth is clogging waterways, inhibiting economic activity and harming the environment on Lake Nokoué and associated rivers. Decisions must be made about hyacinth removal and mitigation.
Stakeholders	• Cranberry farmers • MA Department of Ecological Restoration • Local municipalities • Local & regional NGOs	• Pekalongan residents • Municipal Regional Development & Planning Agency • Universitas Diponegoro • Local NGOs	• Partipants in fishing and acadja practices • Residents of adjacent communities • Green Keeper Africa • National Institute of Water • Local government agencies
System Objectives	• Support competitive sale pricing for land • Support value of restoration projects • Support investment in projects that result in clean water, open space, climate resilience	• Aid in understanding flooding phenomena and related environmental and socioeconomic impacts • Aid in evaluation of flood mitigation policies and interventions	• Profitable harvesting strategy that advances socioeconomic and ecological impact • Technology capacity building
System Forms	• Web-based data exploration tool	• Satellite Remote Sensing Analysis • Decision support system	• Decision support system • Locally operated in-situ water sensor system
System Functions	• Visualize impact of different restoration scenarios • Quantify value of ecosystem services provided by bogs • Identify high priority cranberry bogs for restoration	• Analysis of historical flooding and mangroves • Visualization of socioeconomic data • Predictive risk modeling	• Detect & forecast water hyacinth • Plan harvesting locations • Marketing • Impact evaluation • Build technology capacity

Table 2 Summary of methodologies used by case studies for each EVDT Framework element.

	Massachusetts Cranberry Farming & Bog Restoration	**Pekalongan Coastal Flooding & Subsidence**	**Invasive Plant Management on Lake Nokoué**
Systems Architecture & Stakeholder Analysis	• Qualitative Interviews • Stakeholder Value Mapping • Mapping Stakeholder Needs to System Objectives	• Qualitative Interviews • Local documentation • Primary-Secondary-Tertiary Classification • Mapping Stakeholder Needs to System Objectives	• Qualitative Interviews • Site visits • Review of local non-English Literature • Primary-Secondary-Tertiary Classification • Specifying status quo system architecture & stakeholder roles prior to designing the new system
Collaborative Development	• Formally solicited feedback throughout development • Publicly available code and DSS	• Regular meetings with stakeholders • Formal scenario-based workshops	• Collaborative design of in-situ sensor to be constructed locally • Regular meetings with stakeholders
EVDT Perspective	• E: Land Use / Land Cover Scenarios • V: Ecosystem service estimates and valuation • D: Cranberry farm land use decisions (human-in-the-loop • T: Wetland restoration research	• E: Flooding & Mangrove Analysis • V: Socioeconomic Vulnerability Index Modeling • D: Flood Mitigation Interventions/Policies • T: Observation & Warning System Design Model	• E: Water Hyacinth & Acadja Detection and Forecasting • V: Local benefit of water hyacinth removal & water quality impacts • D: Plan harvesting locations • T: In-situ water quality sensor design
Interactive DSS	• Online • Pre-computed scenario visualizations • Information on individual bogs	• Locally-run • Integrated environmental & socioeconomic visualizations • Computed responses to different interventions	• Online • Near real time data • Forecasting & impact estimation
Reuse & Capacity Building	• Publicly available code & instructional materials	• Reuse of mangrove analysis code from previous projects	• Partnership between MIT and Green Keeper Africa, a local social enterprise, for capacity building

Appendix B (EVDT Diagrams)

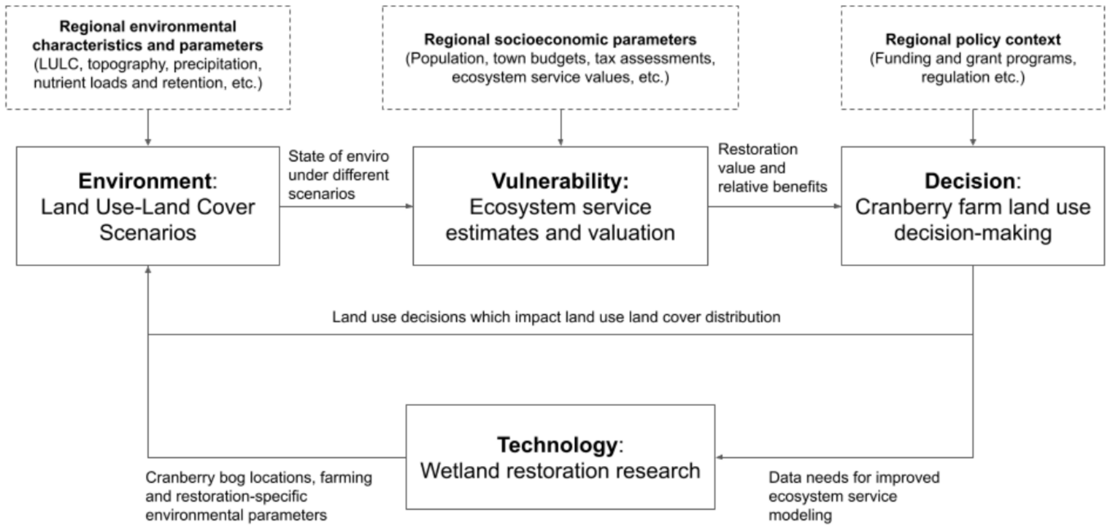

Fig. 9 EVDT Diagram for the Massachusetts Cranberry Farming and Bog Restoration project. Figure from [43]

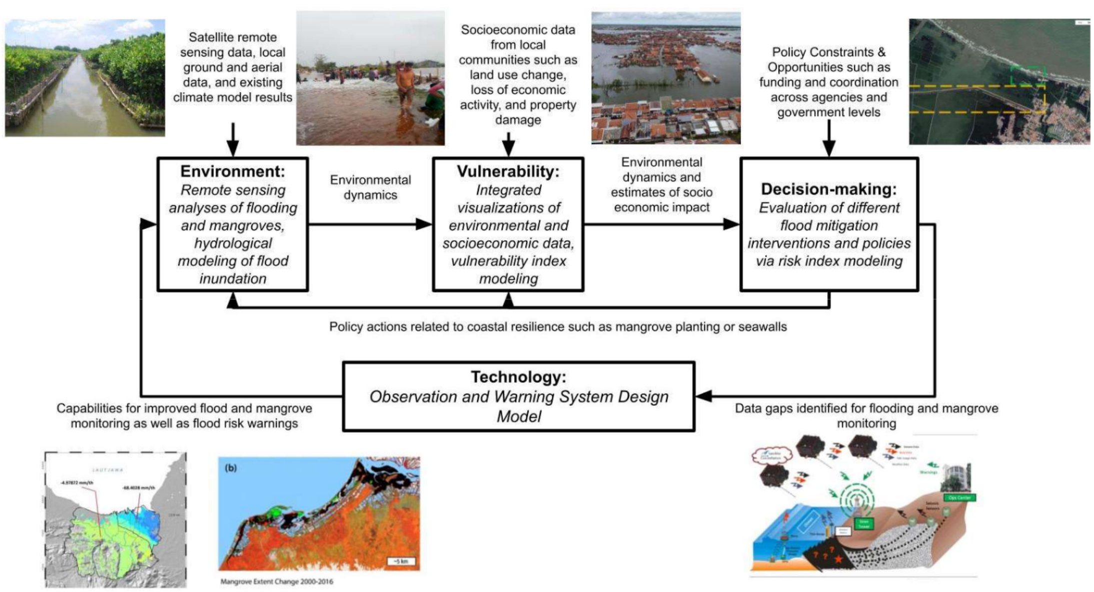

Fig. 10 EVDT Diagram for coastal resilience in Pekalongan, Indonesia. Figure from [45]

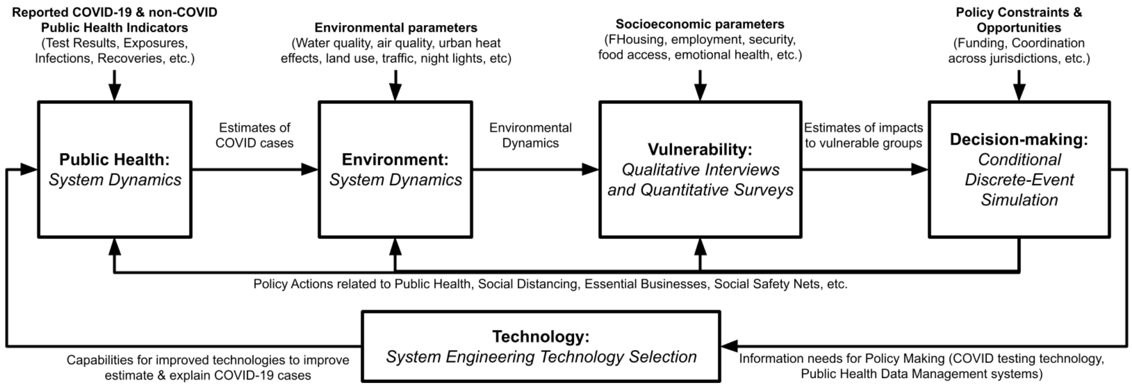

Fig. 11 EVDT Diagram for the Vida COVID-19 pandemic project. Figure adapted from [46]

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