Using Integrated Earth Observation-Informed Modeling to Support Sustainable Development Decision-Making

Ph.D. Thesis Proposal

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Abstract

This work aims to demonstrate the viability of a particular methodology for increasing the accessibility and relevance of earth observation data products to a wider audience of local decision-makers through the development of clearer linkages between environmental modeling and societal impact, while laying the groundwork for a more detailed consideration of (c). To that end, this work centers on exploring the efficacy and difficulties of ***collaboratively developing*** a ***systems-architecture-informed***, multidisciplinary ***geographic information system (GIS) Decision Support System (DSS)*** for ***sustainable development*** applications that makes significant use of ***remote observation data***.

This is done through the development and evaluation of DSSs for two primary applications: (1) mangrove forest management and conservation in the state of Rio de Janeiro, Brazil; and (2) coronavirus response in six metropolitan areas across Angola, Brazil, Chile, Indonesia, Mexico, and the United States. In both cases, the methodology involves the application of the system architecture framework, an approach that has been previously adapted from the aerospace engineering discipline by Prof. Wood for use in sociotechnical systems. This includes using stakeholder mapping and network analysis to inform the design of the DSS in question. Other components of the methodology taken in this work are developing the DSS through an iterative and collaborative process with specific stakeholders; pursuing targeted, related analyses, such as on the value of certain ecosystem services, the value of remote sensing information, and human responses to various policies; and evaluating the usefulness of both the DSS and the development process through interviews, workshops, and other feedback mechanisms.

All of this takes place under the umbrella of the Environment, Vulerability, Decision-Making, Technology (EVDT) Modeling Framework for combining remote observation and other types of data to inform decision-making in complex socio-environmental systems, particularly those pertaining to sustainable development. As the name suggests, EVDT integrates four models into one tool: the Environment (data including Landsat, Sentinel, VIIRs, Planet Lab's PlanetScope, etc.; Human Vulnerability and Societal Impact (data including census and survey-based demographic data, NASA's Socioeconomic Data and Applications Center, etc.); Human Behavior and Decision-Making (data including policy histories, mobility data, and urban nightlight data); 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. This framework is currently being used by several researchers in the Space Enabled Research Group and elsewhere. The capabilities provided by this framework will improve the management 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 model-based systems engineering.

Thesis Committee Biographies

Prof. Danielle Wood

Danielle Wood is an Assistant Professor in the Program in Media Arts & Sciences and holds a joint appointment in the Department of Aeronautics & Astronautics at Massachusetts Institute of Technology (MIT). Within the Media Lab, Prof. Wood leads the Space Enabled Research Group which seeks to advance justice in Earth's complex systems using designs enabled by space. Prof. Wood is a scholar of societal development with a background that includes satellite design, earth science applications, systems engineering, and technology policy. In her research, Prof. Wood applies these skills to design innovative systems that harness space technology to address development challenges around the world. Prior to serving as faculty at MIT, Professor Wood held positions at National Aeronautics and Space Administration (NASA) Headquarters, NASA Goddard Space Flight Center, Aerospace Corporation, Johns Hopkins University, and the United Nations Office of Outer Space Affairs. Prof. Wood studied at MIT, where she earned a Ph.D. in engineering systems, S.M. in aeronautics and astronautics, S.M. in technology policy, and S.B. in aerospace engineering.

Prof. David Lagomasino

David Lagomasino is an Assistant Professor in the Department of Coastal Studies at East Carolina University. He previously studied at Florida International University, where he received a B.S. and a Ph.D. in Geological Sciences, in between which he received a M.S. in Geology at East Carolina University. Lagomasino uses satellite, airborne, drone, and ground measurements to identify areas of coastal resilience and vulnerability. His research links remotely sensed spatial data directly with stakeholders in order to address exposure and sensitivity issues for coastal/wetland management and ecosystem valuation. He has been involved in a number of coastal blue carbon projects with funding from NASA's Carbon Monitoring Systems Program, NASA's Biodiversity and Forecasting Program, USDA's National Forest Inventory Assessment Program, NASA's New Investigator Program, and the Center for International Forestry. His goal is to provide meaningful information that will better inform coastal management practices while also inspiring students and the community to become environmental stewards in order to help sustain our coastal resources. Prior to his current post, he conducted research at NASA's Goddard Space Flight Center just outside Washington, D.C., in partnership with the University of Maryland, to develop models that measure the where when, and why shorelines are the world are changing.

Prof. Sarah Williams

Sarah Williams is an Associate Professor of Technology and Urban Planning at MIT where she is also Director of the Civic Data Design Lab and the Leventhal Center for Advanced Urbanism. Williams' combines her training in computation and design to create communication strategies that expose urban policy issues to broad audiences and create civic change. She calls the process Data Action, which is also the name of her recent book published by MIT Press. Williams is co-founder and developer of Envelope.city, a web-based software product that visualizes and allows users to modify zoning in New York City. Before coming to MIT, Williams was Co-Director of the Spatial Information Design Lab at Columbia University's Graduate School of Architecture Planning and Preservation (GSAPP). Her design work has been widely exhibited including work in the Guggenheim, the Museum of Modern Art (MoMA), Venice Biennale, and the Cooper Hewitt Museum. Williams has won numerous awards including being named one of the top 25 technology planners and Game Changer by Metropolis Magazine.

Glossary

Language in general and technical jargon (of which this glossary qualifies) in particular is intended to communicate. This requires that both the speaker and the listener have some common understanding of the terms used. For this reason, I rarely find it helpful to generate new definitions for commonly used words, except to clarify when there is some significant discrepancies in how the term is commonly used. It is generally preferable to coin a new term if a new meaning is required (see, for instance Myoa Bailey's coining of the term *misogynoir* [1] or the significantly less elegant socio-environmental-technical system in this document).

Decision Support System (DSS): A technical system aimed at facilitating and improving decision-making. Functions can include visualization of data, analysis of past data, simulations of future outcomes, and comparisons of options.

Environment, Vulerability, Decision-Making, Technology (EVDT): A four-part modeling framework created by Space Enabled for use in socio-environmental-technical systems (SETSs) and sustinable development applications [2]. For more detail, including diagrams, see Section 4.1.

geographic information system (GIS): Any digital system for storing, visualizing, and analyzing geospatial data, that is data that has some geographic component. The term can also be used to discuss specific systems, a method that uses such systems, a field of studying focusing on or involving such systems, or even the set of insitutions and social practices that make use of such a system [3]. For more discussion of this definition, see Section 3.3.

Multidisciplinary Optimization: A methodology for the design of systems in which strong interaction between disciplines motivates designers to simultaneously manipulate variables in several disciplines [4].

Multi-Stakeholder Decision-Making: Any decision-making process in which more than one stakeholder must collaborate to reach a decision [5]. This can take a variety of forms, including cooperation, negotiation, voting, or consultation [6].

Observing System Simulation Experiment (OSSE): A method of investigating the potential impacts of prospective observing systems through the generation of simulated observations that are then ingested into a data assimilation system and compared to other real-world data or other simulated data. Most commonly used for remote observation satellite design for purposes of meterology [7] .

participatory geographic information system (PGIS): A subset of GIS that seeks to directly involve the public and other stakeholders, including government officials, non-governmental organizations (NGOs), private corporations, etc [8]. It should be noted that these means involvement in both the production of data and in its application, not merely one or the other [9,10]. This is to be contrasted with the older term, public participation geographic information system (PPGIS), which focuses specifically on the involvement of the public and not that of government agencies or other organizations [8]. For more discussion of this and related terms, see Section 3.4.

Planning: "the premeditation of action, in contrast to management [which is] the direct control of action" [11]. In general, planning tends to concern itself with more long-term affairs that management does, during which it strives for the "avoidance of unintended consequences while pursuing intended goals." Models, and their specific implementations as decision/planning support tools, are one means of achieving this. The term is often prefaced with 'urban' or 'regional' to indicate the specific spatial scale under consideration.

Planning Support System (PSS): A type of DSS specifically designed to support urban or regional planning efforts. These often involve longer time scales and more general/strategic decisions than most DSSs. In general, this work will use the more general term, DSS, and will only use PSS when refering to the literature.

Remote Observation: Any form of data collection that takes place at some remote distance from the subject matter [12]. While there is no specific distance determining whether a collector is 'remote,' in practice this tends to mean some distance of more than a quater of a kilometer. Handheld infrared measurement devices are thus usually excluded (and thereby classified as *in-situ* observatoins. Aerial and satellite imagery are definitively in the remote observation category. Low altitude drone imagery, particularly when the operator is standing in the field of view, is a gray area that is not well categorized at this time.

Scenario Planning: A particular form of planning that focuses on long-term strategic decisions through the represenation of multiple, plausible futures of a system of interest [13]. These futures are often generated by models such as EVDT.

Sustainable Development: The integration of three separate, previously separate fields: economic development, social development and environmental protection [14]. For a more detailed discussion of the history of this term, see Section 3.1.

Socio-environmental System: The complex phenomena that occurs due to the interactions of human and natural systems [15].

Sociotechnical System: Technical works involving significant social participation, interests, and concerns [16].

Socio-environmental-technical System: A system in which social, environmental, and technical subsystems are linked together in such a way that none can be neglected without compromising the modeling, planning, or forecasting objectives at hand. This can be seen as the combination of the terms sociotechnical system and socio-environmental system. Note the particular emphasis on the needs of the observer, not the inherent system itself, as virtually all systems on Earth can be viewed as socio-environmental-technical Systems.

Stakeholder Analysis: Identifying, mapping, and analyzing the stakeholders in a system and their connections to one another in order to inform the design of the system. This involves both qualitative and quantitative tools, such as the Stakeholder Requirements Definition Process [17] and Stakeholder Value Network Analysis [18]. It should be noted that this term is commonly used by systems engineers but is not clearly defined as some specific list of methods. In a Space Enabled context, it commonly refers to the coding of qualitative interviews with stakeholders to elicit such items as needs, desired outcomes, and objectives. These are then often analyzed in some other method, such as Stakeholder Value Network Analysis.

Systems Architecture/Architeting: As defined by Maier, the art and science of creating and building complex systems. That part of systems development most conerned with scoping, structuring, and certification [16]. This tends to refer to the high level form and function of a system, rather than detailed design. Other's, such as Crawley prefer to characterize it as the mapping of function to form such that the essential features of the system are represented. The intent of architecture is to reduce ambiguity, employ creativity, and manage complexity [19]. Arguably this is a more specific formulation of Maier's definition. In general, Space Enabled and I tend to use Crawley's definition, both due to its clarity, and for the various qualitative and quantitative methods that have been developed to work well with this formulation.

Systems Engineering: An interdisciplinary approach and means to enable the realization of successful systems. It focuses on holistically and concurrently understanding stakeholder needs; exploring opportunities; documenting requirements; and synthesizing, verifying, validating, and evolving solutions while considering the complete problem, from system concept exploration through system disposal [20]. For a more detailed discussion of this definition, including its flaws, see Section 3.5.

Tradespace: The space spanned by the completely enumerated design variables, i.e. the set of possible design options [21].

Tradespace Exploration: A process by which various options with a tradespace may be examined and compared in the absence of a single utility function, such as when multiple stakeholders are involved or multiple contexts with no clear priority exist [21].

1 Problem Statement

Over the past two decades satellite-based remote observation has blossomed. We have seen a rapid increase in the number of earth observation systems (EOSs) in orbit [22], significant improvements in their capabilities [12], and much greater availability of the data that they produce [23]. This trend has occurred as part of greater technological and societal trends of increasing data availability, computational power, and modeling ability. Unfortunately, despite some efforts in previous decades [24], this earth observation (EO) data has been largely used only by governments and academics for military and scientific purposes, with the latter focused on understanding and predicting environmental phenomena. Large corporations and NGOs have recently been conducting their own analyses (as seen in the growing industry of climate consultants [25]), but these have required significant expertise and resources, and the results have sadly been mostly unavailable to the broader public.

There is a real need for (a) making remote observation data not just available but accessible to a broader audience by developing data products that are relevant to everyday individuals, particularly those involved in local, rather than national or global decision-making; (b) linking the EO-supported environmental modeling with the societal impact of a changing environment; and (c) putting policy and sensor design decision-making in the hands of a broader population.

2 Research Questions

This work aims to demonstrate the viability of a particular methodology for achieving (a) and (b), while laying the groundwork for a more detailed consideration of (c). To that end, this work centers on exploring the efficacy and difficulties of ***collaboratively developing*** a ***systems-architecture-informed***, multi-disciplinary ***GIS DSS*** for ***sustainable development*** applications that makes significant use of ***remote observation data***. This involves expanding and codifying the previously proposed EVDT Modeling Framework for combining EO and other types of data to inform decision-making in complex socio-environmental systems, particularly those pertaining to sustainable development [2]. Specifically this work will seek to address the following numbered research questions via the listed letter deliverables.

1. What aspects of systems architecture (and systems engineering in general) are relevant and useful for approaching issues of sustainability in complex SETS? In particular, how can they be adapted using techniques from collaborative planning theory and other critical approaches to enable avoid the technocratic excesses of the past?
   a) A critical analysis of systems engineering, GIS, and the other technical fields relied upon in this work
   b) A proposed framework for applying systems engineering for sustainable development in an anti-colonialist manner
2. What are the sustainability benefits of collaborative development of DSSs using the EVDT Modeling Framework in complex SETS?
   a) System architecture analyses of each of the case studies
   b) Development of an EVDT-based DSS for each of the case studies
   c) An interview-based assessment of the development process and usefulness of each DSS
3. What steps are necessary to establish EVDT as a continually development framework, a community of practice, and a growing code repository?
   a) An assessment of lessons learned from these DSS development processes
   b) An outline of potential future EVDT refinement and extension, such as using EVDT to inform the development of future EO systems that are better designed for particular application contexts

It should be noted that these questions are the overarching questions for this thesis. Each case study project is done in collaboration with local partners and is aimed at providing practical benefits. As a result, each case study DSS has its own specific objectives.

3 Background

This section will briefly explain the relevance and importance of each of the emphasized terms in the previous section: ***collaboratively developing***, ***systems-architecture-informed***, ***GIS DSS***, ***sustainable development***, ***remote observation data***. It will start with sustainable development, as this is the primary envisioned application domain of EVDT. It is thus important to justify why this is an application domain worth addressing. This is followed by an explanation of the relevancy of remote observation to sustainable development and why GIS DSS is an important field to draw from. Finally how systems engineering and architecture can be used to tie this disparate threads together will be laid out. Along the way, various limitations and flaws in these various areas will be briefly touched on. The full thesis will dedicate more time to discussing alternative definitions of these terms and various critiques of their underlying concepts.

3.1 Sustainable Development

Sustainable development is here taken to refer to the concerted pursuit of three related (sometimes aligned, sometimes opposed) objectives: economic development, social development and environmental protection. This is in line with the official United Nations (UN) definition, which refers to these three objectives as "interdependent and mutually reinforcing pillars" [14]. On the basis of this definition, intellectual fields and massive multi-governmental interventions have been built, as sustainable development is fundamentally both a "intellectual pursuit" and a "normative outlook on the world" [26]. This concept is important because, despite significant progress in certain domains and certain regions, many individuals and communities are still suffering from severe privations of food, water, healthcare, and more. This is no mere issue of production, but is also connected with issues of allocation (economic inequality is swiftly rising in many parts of the world, including in the author's own country), political mismanagement and oppression, and environmental changes. This work will not detail these numerous concerns (instead I recommend Jeffrey Sach's *The Age of Sustainable Development* for an accessible survey), but it is worth pointing out that the last of these issues, that of environmental changes, is particularly important as it shapes how we can seek to rectify the others. Historical means of economic development (particularly the extensive use of fossil fuels) are no longer seen as sustainable, due to humanity butting up against and even exceeding certain planetary boundaries or capacity limits, as seen in Figure 1, particularly those of climate change, biodiversity loss, ocean acidification, and the nitrogen cycle.

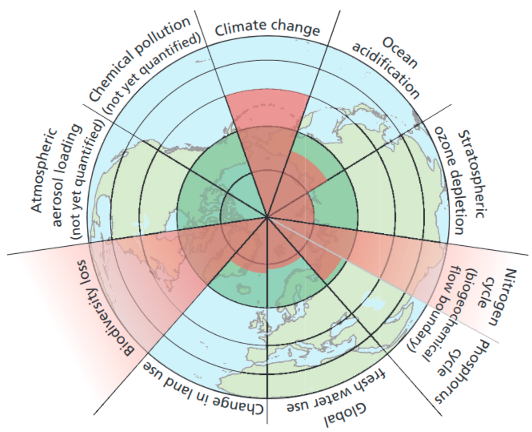

Figure 1: Planetary Boundaries. From [27]

While the impacts of these excesses will be felt globally, they will most heavily fall upon some of the poorer and historically oppressed states, harming those with the least capacity of absorb such impacts and thereby potentially exacerbating global inequality. The spatial variation of the estimated impacts of climate change, for instance, can be seen in Figure 2.

A key reason why these planetary boundaries have been so recklessly exceeded despite the enormous human costs that will result is that these aspects of the environment have historically been both undervalued and poorly understood, at least by those championing economic development. Historically, surveys and quantifications of the natural environment focused primarily, or even entirely, on resources that could be extracted and exploited for economic benefit. In early forest surveys, for instance, "Missing... were all those parts of trees, even revenue-bearing trees, which might have been useful to the population but whose value could not be converted into fiscal receipts" [29]. Just as these factors were missing from accountings of the natural environment, so were they missing form accounts of human society. "Non-human animals are rarely considered within the realms of social theory, and yet... animals can be regarded as a 'marginal social group' that is 'subjected to all manner of socio-spatial inclusions and exclusions.'" ([30–32]as paraphrased in [33]). While these authors were referring primarily to animals, it is also I would argue that this includes plants too, as is particularly evident in the common definition of a weed as a plant growing where it is not wanted.

Fortunately, economists and earth scientists in recent decades have embarked on an effort to better un-

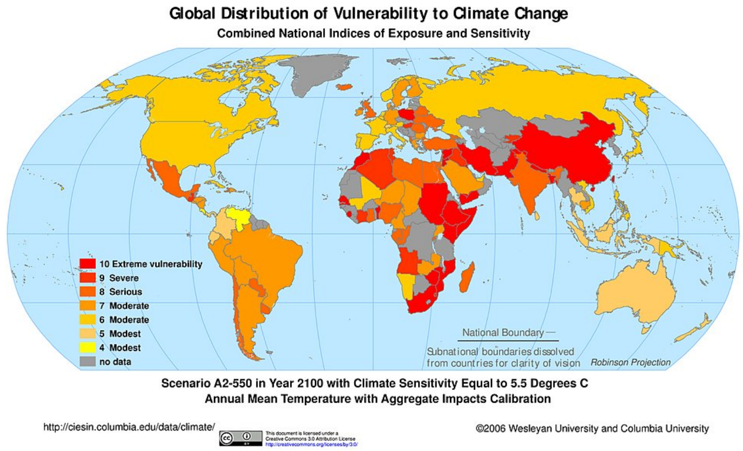

Figure 2: Assessment of global distribution of vulnerability to climate change. From [28]

derstand and catalog such *ecosystem services*, that is to say, the various benefits that humans are provided by the natural environment and healthy ecosystems in particular. Figure 3 illustrates these connections between the environment and human wellbeing, along with the degree to which these connections are mediated by socioeconomic factors. This work has progressed to the extent that there is now a regularly updated database of almost 5,000 value observations of ecosystem services in a wide variety of regions and biomes (though it should be noted that the database overrepresents valuations involving the United Kingdom, inland wetlands, and coastal systems) [34]. Cataloging such ecosystem services is only one step, however. We must also present this data in useful ways to decision-makers so that they may act upon it, as well has provide them with the tools for them to identify additional, uncataloged ecosystem services in their own communities.

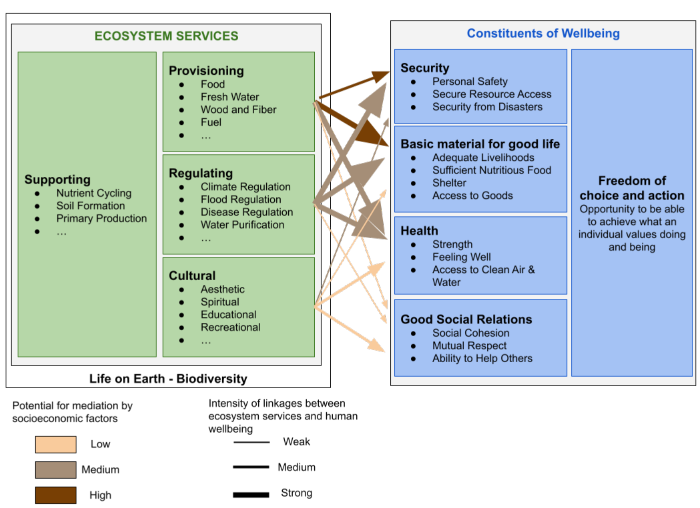

Figure 3: Linkages between categories of ecosystem services and compotents of human wellbeing. Adapted from [35]

It is important to note that, in al these perspectives on sustainable development, a key aspect is the interaction of multiple domains that have historically been considered separately. In this way, the pursuit of sustainable development can considered to be a combination of the established fields of sociotechnical systems [36–38] and socio-environmental systems [15], that many sustainable development contexts can be considered as socio-environmental-technical system (SETS).

3.2 Remote Observation Data

While many of the initial efforts at remote observation from air and space were done with military objectives in mind, scientific, commercial, and social applications soon became abundant. Since much of space-based remote observation in the past several decades has been primarily driven by large governmental scientific organizations, much of that data has been made publicly accessible. An enormous amount of EO satellite data is freely available to the public through 20+ NASA earth science satellites [39], the European Space Agency (ESA) Copernicus Programme (which includes both the 6 Sentinel satellites and in-situ measurements), the various satellites managed by the Japan Aerospace Exploration Agency (JAXA) Earth Observation Center (EOC), the China-Brazil Earth Resources Satellite Program (CBERS), and the satellites of other space agencies.

Social applications of remote observation datat were being considered from quite early on.

By the early 1970s five rationales for using satellite imagery in city planing had become widespread [24]:

1. It offers a synoptic, total view of the complex system in a given area.
2. Satellites provide repetitive, longitudinal coverage.
3. Satellite inventories were more efficient and up-to-date than ground surveys.
4. Remote sensing was objective.
5. Satellites produced digital imagery that could be easiliy combined with ground-based data in novel GISs.

Despite these rationales, or perhaps because of how short reality fell from these rationales at the time, cities and metropolitan areas largely elected not to use satellite imagery for several decades, choosing instead to rely on aerial imagery and ground-based surveys [24]. However, much has changed since the 1970s. The rise of multiple EO satellite companies, including the company Planet's 100+ satellites [40], Digital Global's WorldView satellites, and Astro Digital's ongoing constellation build-out [41], suggests that yet more satellite data is soon to be available for a price. These data sources are likely to be complementary, with the commercial satellites primarily providing visual imagery and NASA satellites primarily supplying other forms of scientific data, though the Moderate Resolution Imaging Spectroradiometer (MODIS), the Visible Infrared Imaging Radiometer Suite (VIIRS), and the Landsat program all capture visual imagery as well. While many of these satellites were designed primarily with scientific purposes in mind, this data is increasingly being used by a wide variety of groups around the world to enable sustainable development and other humanitarian applications, such as forest fire tracking [via MODIS and VIIRS [42]], agricultural monitoring [via Global Precipitation Measurement (GPM) for rainfall [43] and GRACE for soil moisture [44]], climate change vulnerability assessments [via Ice, Cloud, and land Elevation Satellite 2 (ICESat-2) for vegetation and ice monitoring [45]], and many other applications, such as the upcoming Surface Water Ocean Topography (SWOT) [46].

Furthermore, over the course of the past two decades, efforts have been made to systematize the application of remote sensing data to inform decision-making on a host of sustainable development areas. Internationally, over 100 countries worked together to form the Group of Earth Observations (GEO)[1] and 60 agencies with active earth observation satellites have formed the the Committee on Earth Observation Satellites (CEOS)[2]. In the US, the primary source of government unding for such applications is the NASA Applied Science Program, a part of the Earth Science Division, that includes programs focused on disasters, ecological forecasting, health & air quality, water resources, and wildland fires, using data from NASA satellites as well as those of the United States Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA) [47]. The Applied Science Program has clearly learned from NASA past failures of engagement with local decision-makers, and now publish guides on how to ensure that new

[1]GEO, as the name suggests, is dedicated to Earth observation and specifically to the development of a Global Earth Observation System of Systems (GEOSS). In practice this means working together to identify gaps in earth observation and reduce duplication, particularly surrounding sustainable development. In addition to the 100+ national governments, it also includes more than 100 so-called "participating organizations" which include space agencies, NGOs, professional societies, and multiple arms of the UN. For more information see https://earthobservations.org/.

[2]CEOS predates GEO and was pivotal in its creation. Regular membership is primarily restricted to space agencies that operate EO satellites (though other organizations can join as associate members) and its activities tend to focus on interoperability and harmonization. Unlike GEO, all associate members are either government agenices of arms of the UN. For more information, see https://ceos.org/.

projects are actually helpful to users [48]. In keeping with this new mentality, the Applied Science Program, through their Capacity Building portfolio, frequently partners with other organizations, such as United States Agency for International Development (USAID). For instance, both groups worked together to form the Sistema Regional De Visualización Y Monitoreo De Mesoamérica (SERVIR), which provides geospatial information and predictive models to parts of Africa, Asia, Latin America. In a similar collaborative effort, NASA and USAID have also integrated remote sensing data into the Famine Early Warning Systems Network (FEWS NET).

Such efforts have been quite successful in their goals, but have required significant time, expertise, and effort to create and maintain. As overpass frequencies, resolutions, and computational speed have increased, it is increasingly possible to conduct much more rapid, localized, and ad hoc applications of remote sensing data for sustainable development and humanitarian purposes. Within 48 hours and one week respectively, NASA was able to provide maps of damaged areas of Mexico City to Mexican authorities following the 2017 earthquake [49] and maps of damaged areas of Puerto Rico to the Federal Emergency Management Agency (FEMA) following Hurricane Maria [50] (in fact, both of these maps were provided during the same week), through NASA's Disasters Team under the Applied Sciences Program. Such data collection and processing can increasingly be done without the expertise and remote observation systems of governmental space agencies, as demonstrated by a recent effort to conduct near-real-time deforestation monitoring and response [51].

These developments have powerful implications for equity. "The geography agenda is distorted by being data-led... The first law of geographical information: the poorer the country, the less and the worse the data" ([52] as paraphrased by [53]). Remote observation has the potential to help upend this, by providing at least some base level of data globally, with no distinctions for borders or wealth. Increasingly, sustainable development applications of remote observation data are not limited by available remote observation platforms, but by lack of knowledge by potential end-users of its value and by the tools to make use of available data. While data is often available (either freely or at some cost), it is not always readily accessible (particularly in real time) or easily interpreted. Those with the knowledge and capabilities to access and transform this data continue to reside primarily in government agencies and universities (though we have certainly seen heartening growth of such users in a much more diverse set of countries over the past couple of decades). The majority of prominent EOSs are still designed primarily with scientific, meteorological, or military purposes in mind, limiting their utility in more applied contexts, regardless of the creativity of users. And many successful applications of EO data, particularly that which is not straightforward visual imagery, remain squarely focused on characterizing specific, usually environmental, phenomena, such as wildfires [42], aquatic bacterial growths [54], or deforestation [55], with only limited excursions into assessing the connections between such phenomena and human wellbeing.

Due to the obvious potential of such technologies for applications in humanitarian and sustainable development, attempts are starting to be made to quantify the value of various earth observation systems, but many of these have been limited by the inherent difficulties of handling counterfactual scenarios [56]. NASA is well aware of this difficulty, which is why the Applied Sciences Program funded the Consortium for the Valuation of Applications Benefits Linked with Earth Science (VALUABLES) consortium at Resources for the Future (RFF). This consortium is using economic methods to improve estimates of the societal benefits of earth observation. Work by VALUABLES and others has quantified the value of remote observation systems for carbon emission tracking [57], agricultural production [58], and ground water quality [58]. The recent advances in this field are cataloged in the recent publication of a book on the socioeconomic value of geospatial information (which includes more than remote observation) [59]. Integrating econometric models with remote observation system models is useful for both assessing the impact of past missions and for predicting the impact of future ones. Such results can be used to help justify the field as a whole and specific remote observation systems in particular. Many applications, however, require more detailed models that integrate more domains. This is particularly true if the intent is to provide remote observation data to inform operational decision-making.

More is needed to enable the use of EO data for human decision-making in such a way that acknowledges the linkages between the environment and humans. This is major aim of this work.

3.3 GIS and Decision Support

The term GIS refers to any digital system for storing, visualizing, and analyzing geospatial data, that is data that has some geographic component. It can be used to discuss specific systems, a method that uses such systems, a field of study focusing on or involving such systems, or even the set of insitutions and social practices that make use of such a system [3]. This may seem vague, but due to the diversity of its use, it is difficulty to hammer out a more specific definition without excluding important aspects [60–63]. One perspective, however, is to view GIS as the underlying computer systems enabling the middle three components of the broader geographic information science (GISc) methodology, as shown in Figure 4. In that sense, the work proposed for this thesis can be seen as an exercise in GISc spanning all five components, while the specific software produced for this work are instances of GIS.

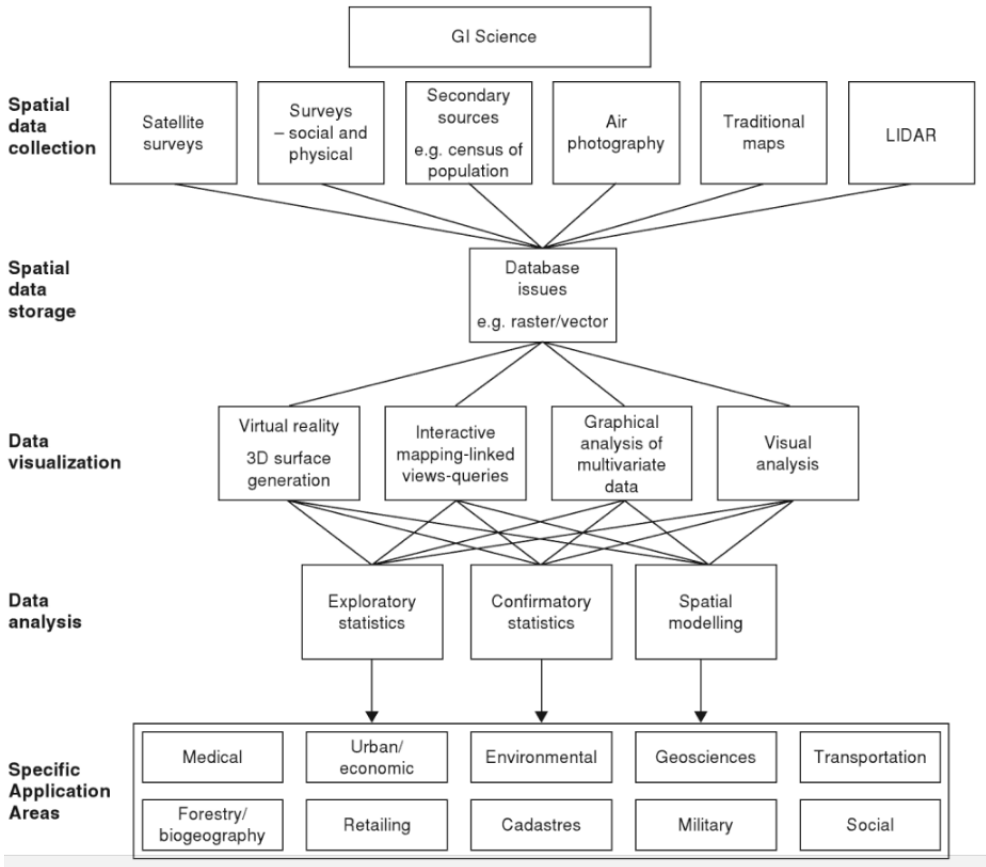

Figure 4: Overview of Geographical Information Science. From [64]

The term GIS and the associated field of study originated in the 1960s and 70s with experimental efforts of the Canda Geographic Information System and the US Bureau of the Census to digitize their demographic and land cover data [65]. It should be noted that these early instances were primarily application, rather than technology driven [66]. The key value of GIS is that it "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" ([67] as paraphrased in [68]).

By 1991, Maguire et al. felt that "it is not fanciful to suggest that by the end of the century GIS will be used every day by everyone in the developed world for routine operations" [69]. This, of course, would turn out to be an understatement, as the world is currently incredibly dependent on GIS. Individuals rely upon the various map applications that we use to search and navigate our world. 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 [70]. Since the turn of the millenium, spatial data has become deeply ingrained economics, urban studies, private industry, social networks, environmental science, public health, criminal justice, and more [71].

One common use of GIS is in DSSs. These are technical systems aimed at facilitating and improving decision-making. Functions can include visualization of data, analysis of past data, simulations of future outcomes, and comparisons of options. Such GIS DSSs are particularly common in development and planning spheres. Planning here refers to "the premeditation of action, in contrast to management [which is] the direct control of action" [11]. In general, planning tends to concern itself with more long-term affairs that management does, during which it strives for the "avoidance of unintended consequences while pursuing intended goals." Models, and their specific implementations as decision/planning support tools, are one means of achieving this.

There is no definitive typology of DSSs, spatial or otherwise, but in general they accomplish some combination of the following functions [72]:

1. *Basic information handling support*
   (a) Information management
   (b) Visual aids
   (c) Group collaboration support
2. *Decision Analysis Support*
   (a) Option modeling (including scenario planning [73]
   (b) Choice models
   (c) Structured group process techniques
3. *Group reasoning support*
   (a) Judgement refinement/amplification techniques
   (b) Analytical reasoning methods

3.4 Collaborative and Open Source

Many of the early applications of remote observation data were technology, rather than need, driven. So it was with the closely related field of GIS as well, leading to powerful critiques by Pickles and others [74]. These critiques 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" [65]. This means that, while collaborations certainly can introduce additional difficulties, such as cultural conflicts, issues of interpersonal trust, effort required to establish rules and norms of participation, they are also immensely rewarding and can improve the results of the work [75].

Second, there was a recognition of the equity concerns at play. 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 [10]. 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" [76]. Meanwhile, academic geographer Matthew Edney argued that, "Without equitable access to GIS data and technology, small users, local governments, nonprofit community agencies, and nonmainsream groups are significantly disadvantaged in their capacity to engage in the decision-making process" ([77] as paraphrased in [78]).

There was thus reason to seek ways to overcoming the limitations of the technology which, as was common sentiment at the time, meant that "for billions the possibility of accessing the best technology and information made available through digital communications network will always be a luxury. Cartographic information, digital or otherwise, becomes a commodity in its mass production and marketing" [79].

In the early 2000s, this desire motivated the growth in interest towards deconstructing current practices and expanding participation. Several names and frameworks were proposed, including Bottoms Up GIS [10], critical cartography [80, 81], GIS and Society [8], and 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 PGIS [8], which also included other stakeholders, including government officials, 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 [9,10]. For example, in Washington state in 2002, several American Indian tribes were using GIS technology to "inventory, analyze, map, and make descisions regarding tribal resources... includ[ing] timber production, grazing and farm land, water rights, wildlife, native plants, cultural sites, environmental data and hazardous site monitoring, historical preservation, health and human resources" [82]. And in 1999, the 'What If?' PSS was created to use "GIS data sets that commnities have already developed to support community-based efforts to evaluate the likely implications of alternative public-policy choices" [83].

PGIS has thus naturally been strongly advocated and widely adopted over the past three decades [84], with numerous frameworks being proposed for how to implement it [85].

Many PGIS implementations still rely upon closed source, proprietary code for the underlying software [63]. Participants may have been able to generate new data and perform analyses, but they often could not access the code itself or change the models directly. This was due to a combination of factors: limited diffusion of programming knowledge; a limited selection of software tools, many of which were closed source; limited access to computers and the internet; and limited collaboration tools, particularly for geographically distributed collaborations [80]. Over the past couple decades however, all three of these limitations have been greatly mitigated (though not eliminated), due to the growth of the internet and the related diffusion of programming knowledge and rise of the open source movement. As two leaders of the *theirwork* PPGIS project in 2011 put it [86],

> The open source movement at its core stands for the development of source code... in a completely open and free way. Pragmatically, this manifests itself as a methodology of making code freely available to anyone who may wish to access it for any purpose, unconditionally. Concurrently, open source is for many a philosophical approach to software development, and is see as the only truly sustainable approach to software development... In both its execution as a model for making possible new forms of collaborative work, and its philosophical underpinnings of sustainability and openness, it is an essential component in and fluence upon a computer-based mapping solution.

This passionate call for open source software is about more than a philosophical ethical stance. It is also about enabling critique and improvements. "Map studies needs to open the 'black boxes' of mapping software, to start to interrogate algorithms and databases, and in particular to investigate the production of ready-made maps that appear almost magically on the interfaces of gadgets and devices we carry and use everyday, often without much overt thought about how they work and whose map they project onto their interface" [87].

It should be noted that some work has placed the responsibility for limited adoption of GIS tools on the planners/users themselves, specifically their lack of will and training with the tools [88]. While this may be the case, this lack of will and training is almost certainly itself due to a lack of outreach on behalf of the tool developers, and thus PGIS is still reasonable strategy to address these barriers. Other challenges around open source tools involve concerns about long-term support. As many (though certainly not all) open source projects are volunteer or academic-driven, changes of interest, financial support, or time availability can have major impacts on the software development and maintenance process. That said, similar concerns can be raised around commercial software products, which can be abruptly cancelled, leaving the users with little recourse. It should be acknowledging that the economics, incentives, and decision-theory surrounding open source vs. closed source software is complex [89], but the continued endurance of open source software (or even thriving, as virtually all servers used for cloud computing are running on open source operating systems [90]), suggests that open source is a viable choice for software projects moving forward.

3.5 Systems Engineering

Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on holistically and concurrently understanding stakeholder needs; exploring opportunities; documenting requirements; and synthesizing, verifying, validating, and evolving solutions while considering the complete problem, from system concept exploration through system disposal [20]. Something missing from this definition is that systems engineering refers to a specific intellectual tradition that arose out of mechanical, civil, electrical, and aerospace engineering fields in the early-to-mid 20th century. It thus tends to draw from an engineering mindset and relies upon engineering techniques, rather than those of urban planning, architecture, or program management. This is important because the nature of systems engineering is that it is inherently abstracted from its subject matter to a certain degree. The tools of systems engineering were developed in order to design hydroelectric dams, rockets, global communications systems, and much more. In this way it is similar to control theory, in that is is not deeply tied to the specific thing being designed or controlled, only to an abstract understanding of its mechanics and relationships. This means that systems engineers, like some physicists, can have a tendancy to see any problem, any situation, as tractable with a systems engineering perspective.

There is a long history of applying systems engineering techniques to development concerns. US Vice President Herbert Humphrey said in 1968 that "The techniques that are going to put a man on the Moon are going to be exactly the techniques that we are going to need to clean up our cities" [24]. In the same year, the RAND Corporation established a multi-year attempt to bring systems analysis and engineering to urban planning. Around the same time, the American Institute of Aeronautics and Astronautics (AIAA) hosted meetings on urban technologies to bring aerospace expertise to bare on the urban crises of the time [24]. It was a heady time, with engineers themselves feeling "that, having reached the moon, they could now turn their energies to solving the problem of growing violence in cities along with other urban "crises" [91].

Almost immediately, however, such grand ideas met with difficulties. While recounting the full history of this trajectory is beyond the scope of this work, one can get a sense of it in quotations from urban planners of the time and since:

> The systems engineers bring some expertise and substantial pretensions to the problems of the city. Their prinicpal system expertise seems to be relative to complex organizations that are mission oriented. There is in any case a good deal of difference between the mission of reaching the moon, and the mission of surival and welfare for soceity and the city. The systems engineer can in general deal best with subsystems and specific tasks, and he therefore suboptimizes. This is a charitable description. [92]

> Trying to solve 'earthly problems,' especially urban problems through aerospace innovations had shown that 'transporting the astronauts from terra firma to land on the lunar sphere, travel hither and yon over its surface, and then back home to Houston' was a comparatively simple task. [24]

Ultimately, reality fell far short of both hopes and expectations, for a host of reasons examined in the literature. [24, 29, 91, 93–95]. This led to the gradual rejection and retreat of systems engineering in development planning. As early as 1973, planning scholars were (perhaps preemptively) eulogizing the death of large-scale models and other tools of the systems engineer [96]. The intervening decades have seen the fields of systems engineering and development planning grow largely independently of one another. Since the 1970s, the urban planning professional has evolved and adopted computational models on their own terms. Interactive DSS abounds [97, 98]. The use of GIS has become the norm [72, 99, 100]., including more participatory variants [8]. Numerous quantative economic and social indeces have been developed [101–105] . Mathematical tools such as cellular automata have become popular [106, 107]. Digital models underly the popular subdiscipline of scenario planning [13, 108]. Interdisciplinary, integrated models have even started to re-emerge [109–111]. Arguably urban planning has adopted many of the tools and methodologies of systems engineering.

At the same time, systems engineering has changed. The belief that systems, even human systems, can be made simple, rational, and controllable has been largely outmoded within the field. Instead, in the guise of theories of complex systems and chaos, they have adopted Jane Jacob's view that "intricate minglings of different uses are not a form of chaos. On the contrary they represent a complex and highly developed form of order." [112]. Complex systems, emergence, systems-of-systems, and complex adaptive systems have all become popular fields of study within systems engineering [38, 113–121], with numerous frameworks being proposed for how to classify and handle such systems [122–127]. Faced with such systems, engineers have had to recognize their own inability to definitively predict the future and have turned to probabalistic methods that instead "manage" complexity over longer time scales, such as epoch-era analysis [128, 129] (which in many ways resembles the aforementioned urban planning method called scenario planning).

Parallel to this, systems engineers have moved away from singlemindedly implementing the directives of an individual client to identifying, mapping, and analyzing the stakeholders in a system and their connections to one another in order to inform the design of the system. This stakeholder analyses involves both qualitative and quantitative tools, such as the Stakeholder Requirements Definition Process [17], Stakeholder Value Network Analysis [18], and qualitative interviews of representatives from different stakeholder groups (something that would have been anathema to the earlier era of systems engineering. In order to translate these complicated networks of stakeholders into designs, systems engineers have developed methods for handling multi-stakeholder negotiation and [5, 130, 131] tradespace visualization and exploration [5, 130, 132–134], the latter of which demonstrates an increased willingness to appreciate the psychology and experience of ther user. The historic preference of the impersonal and 'objective' versus the personal and 'subjective' is by no means unique to systems engineering. It can also be found in economics, jurisprudence, education theory, political science, and even moral philosophy [135]. The development of stakeholder analysis has helped to bridge the gap between these two and thus rectify this traditional deficiency. In fact, the use of stakeholder analysis in contemporary systems engineering is, in a way, a step away from the worldview that sees "human beings as unknowable black boxes and machines as transparent," a viewpoint that "surrenders any attempt at empathy and forecloses the possibility of ethical development" and is a tacit "admission that we have abandoned a social commitment to try and understand each other" [93].

All of this suggests that the fields of systems engineering and urban planning are perhaps more close to each other than ever before, even showing some elements of convergent evolution (see the use of the term complex adaptive system in both fields [136]). Much benefit could be gained through more direct dialogue and collaboration with one another. Why then, do we not see that occuring? After all, several of the critical comments made about systems engineering cited above were from recent years. Part of this is likely historical memory. While decades have elapsed, we are still within a single professional lifetime of some of the excesses of systems engineering. But some concerns can be found much temporally closer. While urban planning is a deeply historical field, systems engineering is not. What histories do exist tend to focus on the engineered technical systems, such as the Apollo program [137], rather than the planning dalliances of the 50s-70s. This is has not gone unnoticed: "One cannot know about the history of media stereotyping or the nuances of structural oppression in any formal, scholarly way through the traditional engineering curriculum of the large research universities from which technology companies hire across the United States. Ethics course are rare" [138]. This can lead to each new generation of engineers using new tools that are attempts to resolve the mistakes of the past, but while maintaining the same tabula rasa mindset that led their forebearers astray. Can one begrudge the urban planner their skepticism when one of the highest profile contemporary applications of systems engineering to planning is the 'urban digital twin' or 'smart city' [70, 139–142] that seems to be a repitions of the belief that "complex controversies can be solved by getting correct information where it needs to go as efficiently as possible," that "political conflict arises primarily from a lack of information," and that "if we just gather lack the facts, systems engineers assume, the correct answers to intractable policy problems like homelessness will be simple, uncontroversial, and widely shared" [93]. This work seeks to chart a different, more history-cognizant path, and thereby capture some of the potential benefit of systems engineering in the sustainable development domain without running afoul of the classic blunders.

One of the key systems engineering techniques that this work relies upon is systems architecture. As defined by Maier, systems architecture the art and science of creating and building complex systems, and in particular that part of systems development most conerned with scoping, structuring, and certification [16]. This tends to refer to the high level form and function of a system, rather than detailed design. Other's, such as Crawley prefer to characterize it as the mapping of function to form such that the essential features of the system are represented. The intent of architecture is to reduce ambiguity, employ creativity, and manage complexity [19]. Arguably this is a more specific formulation of Maier's definition. In general, Space Enabled and I tend to use Crawley's definition, both due to its clarity, and for the various qualitative and quantitative methods that have been developed to work well with this formulation. The Systems Architecture Framework (SAF), as adapted by Space Enabled and previous applied in sustainable development applications [143], involves six steps (after defining the actual system of interest):

1. Describe the Context at international, national, and local levels
2. Identify and categorize Stakeholders

3. Describe Stakeholder Needs, Desired Outcomes and Values
4. Identify Desired System Objectives
5. Describe current Functions and Form
6. Describe proposed Functions and Forms and evaluate them according to the System Objectives

Each of these steps is amenable to, and arguably requires, collaborative participation from stakeholders, linking this methodology to PGIS. Such an approach means that the primary benefits of systems architecture (listed below) [144] do not just accure to central authorities or technocrats, but are held by the community themselves.

1. Architecture is a way to understand complex systems.
2. Architecture is a way to design complex systems
3. Architecture is a way to design standards and protocols to guide the evolution of long-lived systems.
4. Architecture is a way to manage complex systems.

Sustainable development is a pressing need for our world, one that we need our best minds and methods to fulfill. Systems engineering, particularly the new, humbler systems engineering, is well posed to contribute, provided it can maintain that humility. Opportunities for such contributions abound, as nations around the world pursue the Sustainable Development Goals (SDGs) and they increasingly recognize the interconnectedness of our human, technological, and environmental systems.

4 Research Plan

The first two research deliverables, 1a and 1b, are based on literature reviews and the development of written arguments. The former (the critical analysis) has largely been completed and an abbreviated form has been presented in Section 3 (and Subsection 3.5 in particular). Deliverable 1b, the development of a framework has also occured already. This framework is briefly explained in the next section, Section 4.1. The centerpiece of this work, however, are in response to Research Questions 2: the development and evaluation of EVDT DSSs for two primary applications: (1) mangrove forest management and conservation in the state of Rio de Janeiro, Brazil; and (2) coronavirus response in six metropolitan areas across Angola, Brazil, Chile, Indonesia, Mexico, and the United States. In both cases, the methodology involves the application the system architecture framework [16, 19] an approach that has been previously adapted from the aerospace engineering discipline by Prof. Wood for use in sociotechnical systems [145]. This includes using stakeholder mapping and network analysis to inform the design of the DSS in question as well as fulfilling Deliverable 2a. Other components of the methodology taken in this work are developing the DSS through an iterative and collaborative process with specific stakeholders; pursuing targeted, related analyses, such as on the value of certain ecosystem services, the value of remote sensing information, and human responses to various policies; and evaluating the usefulness of both the DSS and the development process through interviews, workshops, and other feedback mechanisms. Finally, to address Research Question 3, lessons learned will be identified and a future development path for EVDT will be laid out. The following subsections will go through each of these steps in more detail.

4.1 EVDT Framework

The EVDT Framework is process for developing a DSS for a sustainable development application. This processed is characterized by five basic elements:

1. The use of systems architecture & stakeholder analysis to identify needs, design the DSS, and understand the context. This requires significant engagement with as many of the stakeholders as is feasible.
2. Collaborative development of the DSS that continues that stakeholder engagement.
3. A concept of the sustainable development application as a complex SETS, typically involving the Environment, Human Vulnerability and Societal Impact, Human Behavior and Decision-Making, and Technology Design. This concept undergrids the DSS architecture.

4. An interactive decision-support system. This can take the form of an in-browser page or a standalone application for a computer or phone.
5. A consideration towards modularity and re-use of DSS components in future applications.

To elaborate further upon Item 3, an EVDT DSS integrates four models into one tool: the Environment (data including Landsat, Sentinel, VIIRs, Planet Lab's PlanetScope, etc.; Human Vulnerability and Societal Impact (data including census and survey-based demographic data, NASA's Socioeconomic Data and Applications Center, etc.); Human Behavior and Decision-Making (data including policy histories, mobility data, and urban nightlight data); 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 5, 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 [111].

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, as has already been described, 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 [146].

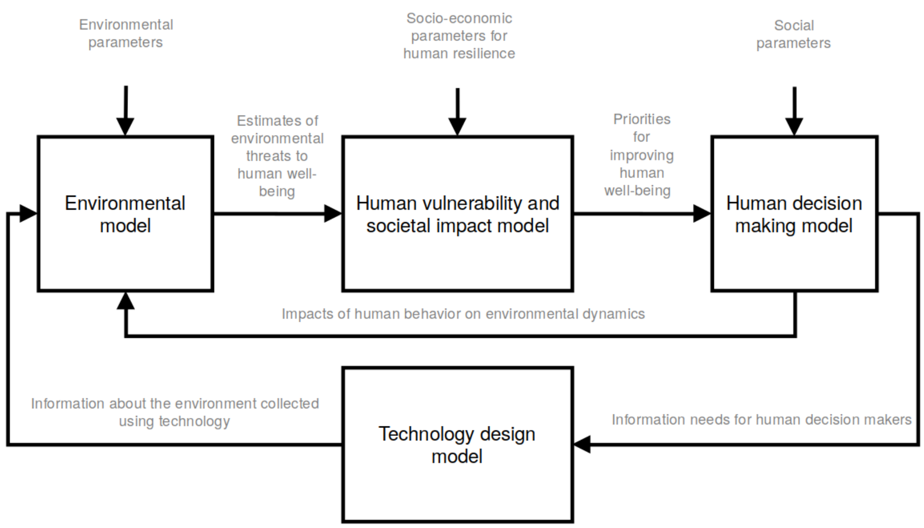

Figure 5: Baseline version of the Environment - Vulnerability - Decision - Technology Model (Generic Case)

This set of four models with the particular linkages shown in Figure 5 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 the user themself substitute for the decision-making model) or omitting a model altogether. For other applications, it may make sense to conceptually break a model into two or more components. In the Vida project, 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 arrangment of EVDT components is to consider what questions the user or researcher is seeking to answer with this application of EVDT. For instance, the default EVDT arrangement shown in Figure 5 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 use of collaborations.

4.1.1 EVDT Novelty

It is important to establish what aspects of EVDT are novel and how this framework relates to the curren state of practice.

Computational models have long been closely linked to the pursuit of sustainable development and with its definition, stemming from the World3 system dynamics model underlying the Club of Rome's *The Limits to Growth* report in 1972 [147]. As was discussed in Section 3.5, the development field would largely come to repudiate such efforts in the mid-to-late 1970s, only to come back around to modeling on their own terms in the subsequent decades. Thus it cannot be said that EVDT is new in saying that modeling plays an important role in sustainable development.

Nor can it be said that EVDT is the first to advance the concept of multidisciplinary, integrated models in development applications. To refer to just a handful of examples:

- The open source UrbanSim combines land use, transportation, and certain environmental factors in a dynamic, area-based simulation system that, similar to EVDT, is a collection of multiple models [97].
- The agent-based Integrated Land Use, Transportation, Environment (ILUTE) model simulated the urban spatial form, demographics, travel behavior, and environmental impacts for the Toronto area [148].
- The TripEnergy model combines an environmental submodel (transportation systems) and societal impact submodel (energy consumption and emissions of vehicles) [149]. It is then combined with a model of human decision-making to create Tripod, "a smartphone-based system to influence individual real-time travel decisions by offering information and incentives to optimize system-wide energy performance" [150].
- The closest attempt to what we are proposing 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 combinging 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 in EVDT. Their example is also proof that the kind of loose integration of library of models that EVDT envisions is possible [111].

In the field of earth science, integrated models have also become increasingly common. Originally developed for operational weather forecasting, OSSEs have found widespread use for designing earth observation systems at NASA and elsewhere [7], by linking models of environmental phenomena with simulations of observing platforms (both hypothetical and real). These models are rigorously validated [151] and are often custom-made for a particular mission. Significant progress has been made however by the Hydrological Sciences Laboratory and Earth Science Technology Office at NASA in developing the Land Information

System (LIS), a more reusable and inter-operable modeling tool with numerous earth sciences applications (soil moisture, hydrology, meteorology, etc.) [152]. One of these uses is the easier development of OSSEs, as a means of facilitating technological development. Since the development of the LIS, the Hydrological Sciences Laboratory has worked to make the earth science models more accurate, utilize a broader range of computational methods, and standardize the validation and evaluation processes for OSSEs.

All of this clearly demonstrates that I am far from the first to argue that such multidiscplinary integration is necessary, nor to recognize that it is easier said than done [111]. What then, does the EVDT framework specifically have to offer?

First, there is the developmental process and theoretical underpinnings of EVDT: the combination of systems architecture (and other systems engineering techniques), GIS, collaborative planning, and remote observation. As was argued in 3, these fields each of complementary aspects that can be brought to bear in the development of future DSSs.

Second, there are distinct advantages to the development and codification of a concrete framework for such integrated modeling projects for sustainable development applications. Many of the above examples of integrated models were developed either without such a framework at all (a one off model intended to solve a particular problem or demonstrate a particular technique) or for a different class of applications (the OSSE framework is fundamentally about designing better EOSs for scientific purposes). Those few that have both a dedicated framework and a sustainable development focus (this includes SERVIR, FEWS NET, and various UN-affiliated programs such as the World Food Program) are intended for large governmental (often multi-nation and/or multi-agency) teams and typically are aimed at national or even multinational applications. There is a real need for a framework that is dedicated for sustainable development applications of small scales, accessible to relatively small teams for specific, targeted projects. The EVDT framework has the potential to fill that gap. Research Question 1 is aimed at developing the EVDT Framework in detail and identying these advantages. Research Question 2 is then aimed at demonstrating these advantages.

4.1.2 EVDT Intended Applications and User Types

EVDT is not intended to be an exclusive project of Space Enabled. It also not intended to be a framework used by isolated individuals. We actively invite involvement from other systems engineers and those from other disciplines. Through this proposed thesis and other related projects, the framework will be refined, initial applications demonstrated, a basis of code built (already available online [153–155]), and a community of collaboration sprouted. These will can be built upon for building a community of practice, where individuals can contribute in a variety of ways, as shown in Figure 6.

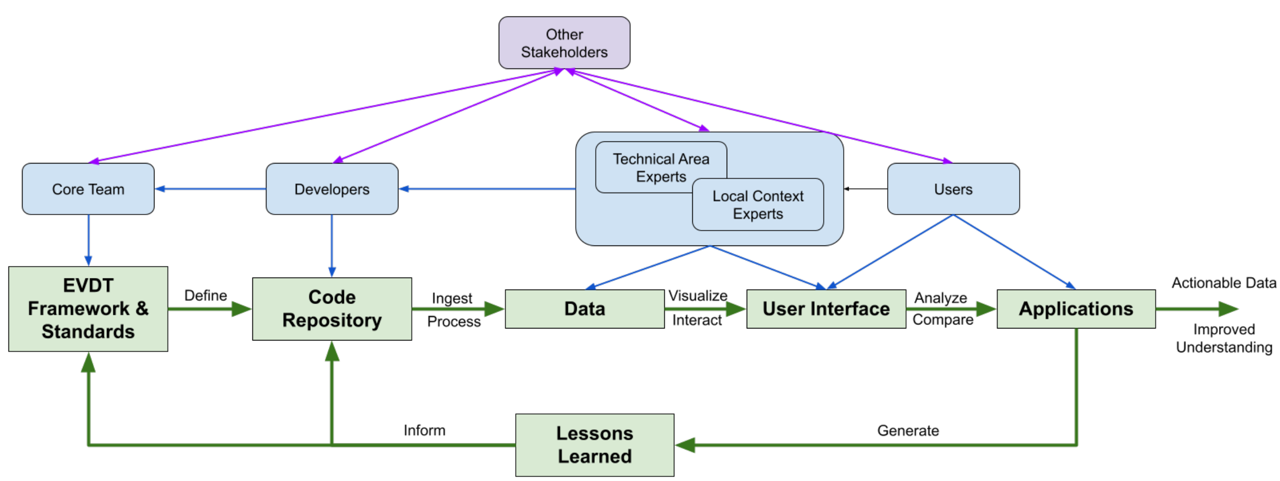

Figure 6: The EVDT development pipeline. Note that the different community groups, shown in blue, are not necessarily discrete and one individual could simultaneously participate in multiple.

It is worth further describing some of the categories of EVDT community members shown in the blue boxes of Figure 6. What follows will be a generalized discussion of these categories. Specific instances for this thesis are discussed in Section 4.2.

Moving from left to right, the *Core Team* refers to those directly involved in the development of the EVDT Framework. Right now this is essentially a set of researchers in Space Enabled and some close academic affiliates. This team is likely to remain predominently academic moving forward, though could transition to involving individuals or organizations from NGOs in the future. The members of this team will typically have expertise with sustainable development and DSSs, significant experience with EVDT, and investment in its success. Particularly once EVDT is more developed, this core team is likely to be formally defined.

The *Developers* includes all those who actively develop the models, user interfaces, visualizations, and other associated aspects of the DSS software for the various EVDT projects. These will typically be individuals with expertise in GIS, coding, and/or data processing. Thus they are likely to work in academia or as analysts in a government agency or NGO, though the project will be open source, membership in this category will not be formally defined and participation will be encouraged at any level of expertise or degree of involvement. Currently the Developer team is largely the same as the Core Team, though we have some developer involvement from other collaborators as well.

Technical Area Experts refers to experts in some relevant domain to an EVDT project but are consulted but not directly involved in the ongoing development of the EVDT Framework and code repository. This could include individuals such as ecosystem services economists, human mobility researchers, or fisheries experts. They will typically come from the ranks of academia, though it is not unreasonable to expect some number of government analysts or NGO researchers.

Local Context Experts refers to those who have a high level of knowledge of the SETS and stakeholders of a particular EVDT project. This could include a local community leader, an experienced activist, or a local government official. This category is grouped together with *Technical Area Experts* as the line between the two is oftentimes blurry. A local university researcher who studies the economics of informal housing and who specializes in the city involved with a particular EVDT project is arguably both a Technical Area Expert and a Local Context Expert.

Users refers to those who directly use the DSS software developed through an EVDT project. Exactly who these are will depend on the specific project and thus their level of experience with mapping, earth science, or development may vary significantly. They should be direct stakeholders in the specific EVDT project and have some involvement with the decision-making process (though not necessarily formal involvement).

It should also be emphasized that while Figure 6 is fairly linear, the EVDT Framework emphasizes collaborative development. One person may serve multiple roles in the pipeline and, even if not, stakeholders, including users, should be involved throughout the DSS development process.

As the number of applications increase and the code is refined, the various models used in the applications may themselves be the first members of an openly accessible library of models. Potential user groups could adapt and reuse EVDT components in other applications, without having to start from scratch. Initially this would likely still require significant code expertise, but it is entirely possible for functionality to be created to allow for 'plug-and-play.' A user may be able to, in browser or on desktop, select a geographic area of interest (e.g. the Sóc Trăng Province of Vietnam), select an environmental model (e.g. coastal forest health), a societal impact model (e.g. cyclone vulnerability), a decision-making model (land use conversion and conservation policy), and a technology model (satellite versus in-situ monitoring), all without writing a line of code (though perhaps being required to import new datasets themselves). Such functionality, along with the recruitment pipeline shown in Figure 6, help to expand participation in all aspects of EVDT. In this way the user base will be expanded beyond initially invested experts.

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 model interoperability standardization, the code moderators will need to specify accessibility norms as well, so as to ensure usability by individuals with a wide range of backgrounds. Existing prototypes have made some steps in this direction, 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 some more targeted efforts may be required in the future to specifically recruit translators for targeted languages.

Language is not the only accessibility barrier, however. Terminology, presentation, and interactiveness can also be differentiately accessible to different individuals, depending 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.

Another consideration in the future of EVDT are the types of applications that it will be used for. 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 casaul 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, as shown in Figure 7. For instance Items 3 and 4 (best served by configuration B of Figure 7) 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 (configuration A) 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 better serve the needs of the Item 1 user.

Ideally, EVDT would 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 and consideration with the EVDT community.

It should also be recognized that not all users will engage with the EVDT DSS software products directly or in the same way. As shown in Figure 6, some stakeholders and community members will participate in the SAF process, but may not directly interact with the EVDT software products themselves. This is both due to the fact that many people are unlikely to have the time or inclination to do so (understandably so) and due to various barriers that will doubtlessly remain despite the efforts of EVDT developers. Such barriers include access to the internet, computing power, and electricity. While all of these are becoming available to an increasing number of people globally, they are by no means ubiquitous. Initial prototypes have EVDT have pursued both offline, desktop version and online, browser-based versions to try and accomodate different levels of resource access. Such issues will need to be considered as part of future development decisions as well.

Finally, this envisioned development and expansion process is fundamentally a "snowball model." Existing team members collaborate with new partners and their communities. This results in additional team members who can then collaborate with others. EVDT may (and should aim) to one day be easily accessible even in the absence of connections to existing community members, but that is not in the immediate future.

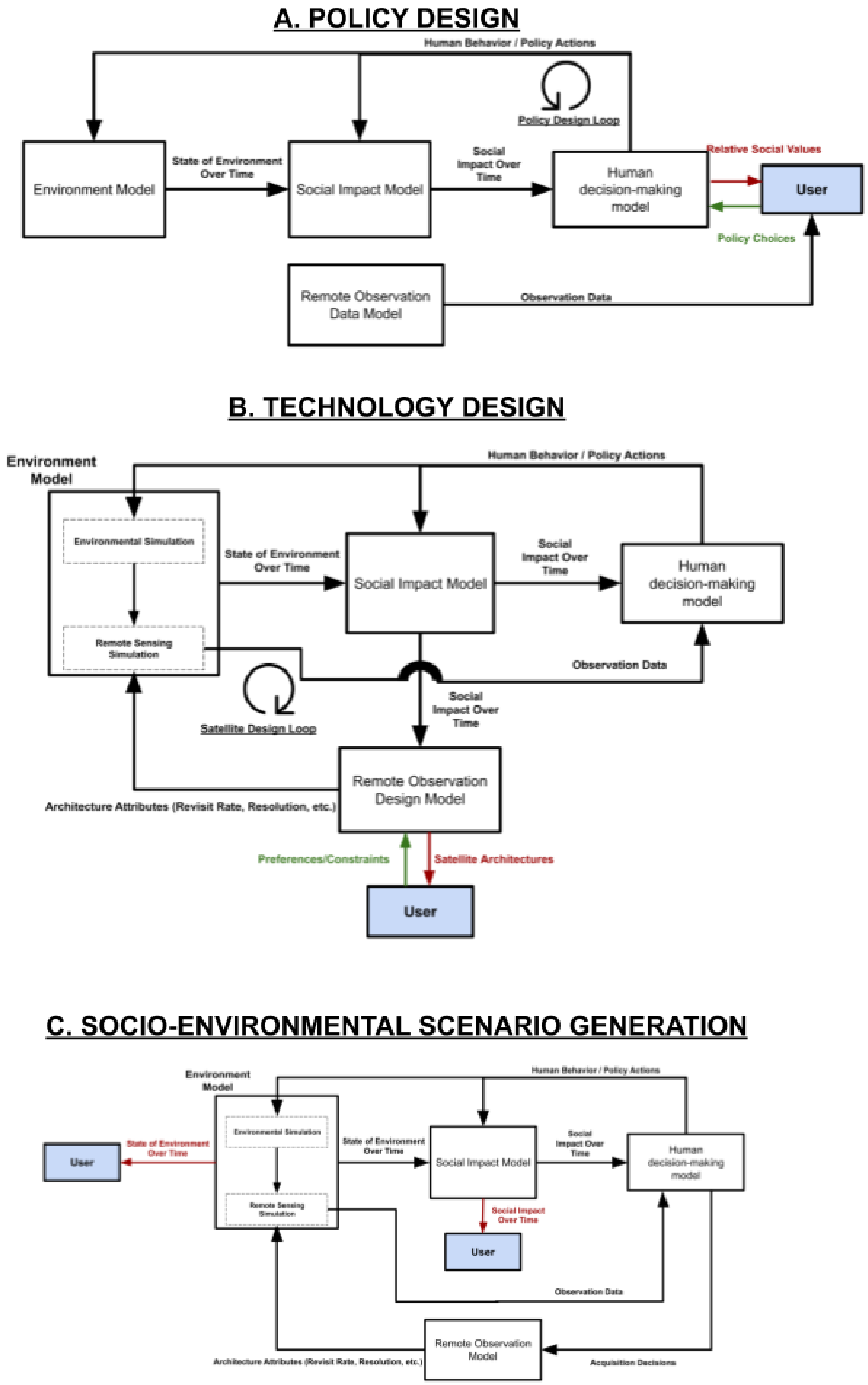

Figure 7: Three example EVDT research configurations.

4.2 Case Studies / Study Areas

While EVDT does not include any concrete spatial scale requirements, it is often the most straightforward to apply to it at a a relatively local scale, like much of the early history of GIS applications [75]. Most of the applications to date have been at the area of a metropolitan area or that of a small province. The most promising applications tend to be at intersections of rural and urban areas. Urban areas often depend on an area significantly larger than the built-up area for basic resources and ecosystem services, particularly for water, bulky materials, and waste disposal. I will not attempt to strictly define rural and urban here, as the "distinctions are often arbitrary" [156]. Instead this work will rely upon local definitions of urban, rural, and peri-urban, similarly to the UN [26].

4.2.1 Rio de Janeiro Mangroves and Fishing Communitites

Guaratiba is a relatively rural district of Rio de Janeiro situated in the southwestern corner of the municipality. It is home to a mix of land uses, including decorative plant farming, multiple fishing communities, a military base and training center, a state-run biological reserve, some informal settlements, and a growing ecotourism industry. The biological reserve exists to protect the largest remaining mangrove forest within the municipality. These mangroves are vulnerable due to landward urbanization, including a recently opened urban transit line, and rising sea levels [157] They provide a variety of ecosystem services, including serving as a mechanism for highly efficient carbon sequestration, supporting a small-scale industry of fishing and crab catching, preventing coastal erosion, and attracting the aforementioned local ecotourism industry [158]. Government policies to conserve the mangroves can use integrated modeling tools to consider both the benefits of protecting the forests as well as the economic needs of low-income communities. This, coupled with the Rio de Janeiro municipal government's pre-existing interest in generating useful datasets and making them available online through the Data.Rio platform [159], made the Guaratiba mangroves a particularly suitable case study for the EVDT Modeling Framework.

Our primary Local Context Experts and points of contact are at the Pereira Passos Municipal Institute of Urbanism (IPP), which is the municipal data agency, and ESPAÇO, a research group at the Federal University of Rio de Janeiro (UFRJ) who study various coastal ecosystems in Brazil and elsewhere [160, 161] and who are also familiar with examining socioeconomic impacts of environmental phenomena [158]. The latter can also be considered to be Technical Area Experts. Other Local Context Experts include a member of a local fisher association and government officials at the municipal urban development agency and the municipal environmental agency Additional Technical Area Experts include two ecosystem services economists (one from the University of West Virginia and one from RFF) and arguably the committee members for this thesis. The primary intended users for this case study are government officials at the IPP who have a fair amount of experience with mapping. Future projects in this area would ideally expand that userbase to non-government individuals. This project began in 2018 and since that time Jack Reid made two multi-week field visits to Rio de Janeiro and Guaratiba in particular.

4.2.2 The Vida COVID-19 Response Project

As the coronavirus pandemic swept the globe, many of the local points of contact working with Space Enabled on EVDT and other projects had sudden changes in priorities. Several of them raised the possibility of adapting and expanding the EVDT Modeling Framework to approach coronavirus-related decision-making and impact analysis. This seemed relevant because, as others have noted, coronavirus impacts and response can be characterized as a complex system warranting a multi-domain, model-based approach [162]. The second case study will focus on this project, which ultimately became known as Vida and came to involve six metropolitan areas across Angola, Brazil, Chile, Indonesia, Mexico, and the United States. In each of these areas, Vida was (and is) developed in collaboration with local government officials, university researchers, and general community members.

Whereas the first case study focuses on simulating the changes in mangrove forest over decades, the focus of Vida is examining hourly to weekly air and water quality data alongside daily coronavirus epidemiological data and weekly quarantine policies. Government officials need actionable data to both address the ongoing public health crisis and to cope with the resultant socioeconomic and environmental consequences. Community members need to understand why their government is making the decisions that it is and understand the risks associated with their own actions. The Technical Area Experts on this project include researchers from Harvard Medical School. Meanwhile the Local Area Experts (many of whom are technical experts in their own right) include a mix of government officials and academic researchers, most of whome work in the public health and/or in GIS. The intended Users are those same individuals as well as the various public health agencies / task forces that they are affiliated with. In general, the concept is for our partner organizations to use EVDT to develop analyses and presentations that can inform pandemic response. The exact process by which this takes place varies from location to location.

4.3 Development and Evaluation

It should be acknolwedged that these projects are actively underway, so some parts of the development process described here have already been completed, either partially or in full.

In keeping with the SAF steps outlined in Section 3.5, each of the case studies begins with discussions with potential collaborators who are local to study area. These conversations serve to outline the general scope of the study area (and therefore the system boundaries) and identify other stakeholders. This transitions smoothly into more formal qualitative interviews with representatives of the various stakeholder communities to elicit needs, relationships with other stakeholders, and general perspectives. These are used to construct stakeholder maps which can then be analyzed to identify the DSS goals and requirements, as well as the context constraints that it will be operating in [19, 163]. We also seek to understand the history of the area both environmentally and socially, in order to understand the existing systems that we are intervening in, rather than assuming that each location is a sustainable development tabula rasa. The Space Enabled philosophy of research (and thus of EVDT) involves a level of participation and collaboration that goes beyond stakeholder analysis. By paring complex SETS theory with such collaborative planning theory, we can thereby avoid many of the traditional problems of systems engineering [13].

One of the key objectives of the stakeholder analysis process is to collaboratively assess data availablity, identify gaps, and select preferred datasets. For example, if Land-Cover and Land-Use (LCLU) datasets are deemed relevant to decision-making in a particular context, numerous options are often available that vary significant in resolution (spatial and temporal), specificity of classes, and accuracy. The last can be particularly worth considering when applying global datasets (eg. Giri's mangrove map [164]) to particular regions, as global accuracy does not necessarily imply accuracy in all regions. For example, approximately 63% of studies of mangrove-related ecosystem services are focused on parts of Asia despite these regions constituting providing only 38% of the world's mangrove coverage [165]. One would naturally expect metastudies of mangrove-related ecosystem services to be most accurate in Asia. Local collaborators can often provide maps and other data generated by local community members or government agencies. These can be compared with the global datasets to assess local accuracy and, if time and resources can be allocated for it, in-situ validation and calibration. In some cases, gaps in available data may be identified and strategies developed to either address them or work around them.

In the Rio de Janeiro Mangrove case, for example, plentiful data was available regarding LCLU, including specifically for mangrove extent. Locally developed LCLU maps were created from a mix of in-person surveying and commissioned aerial surveys every 2-3 years for the past few decades. Several, highly accurate and highly validated global mangrove extent maps exist for various points in time, including the aforementioned Giri [164], Global Mangrove Watch (GMW) [166], and Tropical Morest Forest [167]. There also is the Brazil-specific Mapbiomas (which also includes numerous other LCLU categories) [168]. The local maps have the highest spatial resolution and best accuracy, but is only available inconsistently across time. Mapbiomas has consistent annual coverage from 1985 to 2020, coupled with the fact that is was specifically designed and calibrated for Brazil. Tropical Moist Forest, meanwhile has similar temporal coverage and resolution, and also distinguishes undisturbed forest from degraded forest. Thus deciding which, or which combination, of these datasets to use in the case study (or to create a new one ourselves) has to be based on meeting the needs of the stakeholders and take place via discussions with those stakeholders.

Opposite to this is abundance of readily at hand applicable data is information regarding the local ecosystem services value of the mangrove forests. While excellent (though not perfect) data is available on the carbon storage and sequestration levels of mangrove forests (a global ecosystem service) [169, 170], estimates for the other forms of ecosystem services provided by mangroves (including water filtration, phosphorous and nitrogen sequestration, and on-site and off-site fishery habitat support) vary significantly from study to study and region to region [171–174]. What studies that exist for the Rio de Janeiro study area in particular tend to focus primarily on carbon [175], examine a singular point in time [175, 176], or contain primarily qualitative data [176]. None of these are without there uses, but neither do they directly address the need for a better understand of the local ecosystem services provided by mangroves in this context. There is thus a need to identify what steps can be taken to fill this gap (while still acting within the resources available for this project). These data-generation activities themselves become part of the DSS development process.

Once stakeholder needs, desired outcomes, and values are described, work begins on the actual DSS. During this process, ongoing meetings with a diverse set of stakeholders continue in order to receive feedback on prototypes, elicit new useful datasets, identify additional needs, and encourage direct contribution to the DSS code (when desired by the local collaborators). In this way, a certain level of evaluation takes place throughout the development process. Nonetheless, additional validation is required.

For each component of EVDT, internal validation work is best conducted according to the norms and standards of that field. For the Environment Model in the mangrove case, for example, this entails working with ESPAÇO using both remote sensing and in-situ monitoring in order to calibrate and confirm the results of the mangrove health tracking discussed earlier. In the Vulnerability submodel, the data will be used to identify the best computational method and theoretical approach to modeling the impacts of mangrove health on local communities. Data in each of the submodel domains has various sorts of inherent error, but these can be mitigated through relying primarily on well refined methods and datasets, as well as by clearly documenting and acknowleding what errors exist. Another potential source of error here is that I am not an expert in all of the relevant fields, though over the course of my education, I have striven to gain at least *some* experience with each of these disciplines. This is further compounded by the fact that I have limited familiarity with the various locations and communities involved in the case studies. This difficulty will be overcome by a combination of humility with regards to the subject matter and reliance on partner organizations and subject matter experts. This is in fact one of the chief benefits of the collaborative methodology proposed, as it does not rely upon nor assume that the external researcher is all-knowing.

In addition to this component-by-component verification work, however, there is also a need expressed by Deliverable 2c for overarching validation of the EVDT Modeling Framework and its specific instantiation in a particular context. Through the stakeholder analysis process described above, target audiences can be identified and then engaged either individually or as cross-audience groups. The original research plan called for directed workshops to assess validity via the collection of methods known as purposeful gaming [177], wargaming [178–180], and role playing gaming [181, 182]. The COVID-19 pandemic has impacted the feasibility of convening such workshops, so evaluation may rely more heavily on stakeholder interviews (individual and/or group). If this occurs, it would push full workshop evaluation to future EVDT projects, of which there are several in the works. Either way, there are two primary forms of error likely occur in this process. The first is limited generalizability due to a limited sample size, both in terms of stakeholder interviews and in terms of case studies. Only so many involved stakeholders will be able to be interviewed. This in turn restricts the forms of statistical analysis that can be performed and the degree to which a universal claim can be made and raises concerns that, even benefits of this framework can be demonstrated for these particular stakeholders, that might not be true for all or even a significant portion of current and potential users. This is of obvious scientific concern, but also of practical concern, as minimal generalizability would threaten most of the potential impacts of the framework. This threat can be partially mitigated by selecting diverse case studies and through the use of detailed qualitative interviews to supplement any quantiative analyses.

The other form of likely form of error is due to subject bias. Particularly for the partner organizations, the users will likely have some history with the Space Enabled group and some vested interest in seeing the group and this project in particular succeed. This could influence their interview responses. Qualitative interviews can be beneficial here as well, as they can provide more insight into the interviewee's state of mind than simple quantitative scores.

Overall, this thesis will be aimed at developing the EVDT Framework in general and demonstrating its ability to identify and fulfill the needs of system stakeholders and users. While evaluating the specific DSS software and analytic products is an important part of evaluating the framework as a whole, it is not the primary focus of this work. Future research projects by myself and others in the EVDT community (including some actively underway projects in Space Enabled) will further refine the framework, evaluate different use cases of the EVDT DSS software products (e.g. solo use, guided workshops, etc.), develop additional component models, and improve modularity and reusability.

One key aspect to note about scope and intent here, is that the case studies in this thesis are intended to provide data products, visualization, and modeling methods that may support local policymaking. They are not intended to generate specific policy recommendations as an outside expert, nor to deliver fully operational versions of the DSSs.

5 Expected Results and Contributions

This section will provide some more detail on the primary research deliverables listed in Section 2. Each stage of the research plan will result in specific, concrete products.

1a. The critical analysis of systems engineering and related fields as methodologies in a sustainable development context will provide a theoretical underpinning for this research endeavor overall and will inform any necessary changes to the research plan. Research Question 1 is aimed at developing an adaptation of systems architecture that draws on collaborative planning theory for improved participation and thus of enhanced social justice. This can only be done by first conducting such a critical analysis and clearly identifying the potential points of improvement.

1b. The proposed anticolonialist framework itself flow directly from the previous deliverable. This the the EVDT Framework, including stakeholder analysis, the collaborative development process, and the four component models. This will constitute the primary theoretical contibution of the thesis and will be useable by GIS DSS developers in a variety of sustainable development applications. Research Question 2 can be viewed as an application, demonstration, and evaluation of this contribution.

2a. The stakeholder interview and need identification process will result in stakeholder maps (an simplified example of which is shown in Figure 8) and associated analyses. These in turn will directly inform the systems architecture, a high-level example of which can be seen in Figure 9. Both of these are continuously refined during the collaboration process.

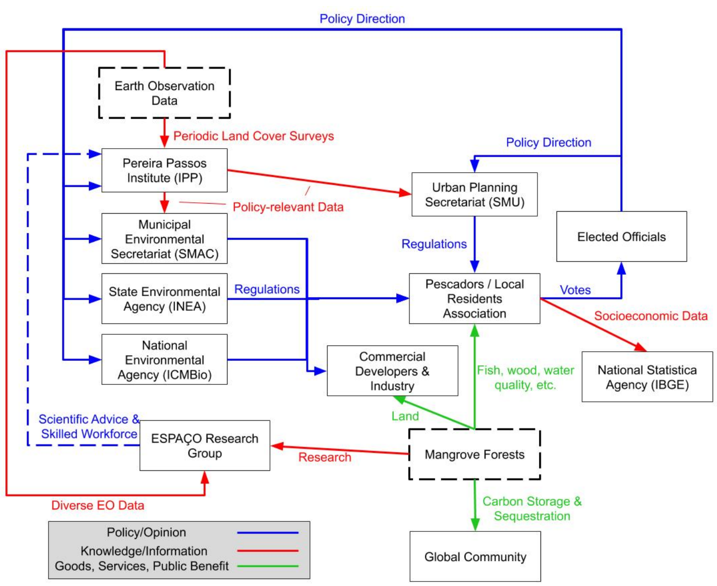

Figure 8: Stakeholder Map for the Mangrove Forests of Rio de Janeiro

2b. The DSS development process will result in both intermediary and final products. The intermediary products include EVDT-component analyses, such as assessments of mangrove health and extent over time, and the identification of inter-component linkages, such as quantifications of mangrove ecosystem services or the quantification of the impacts of COVID-19 on human activity as measured by urban night-lights and telecoms mobility data. Final products include the prototype DSS software themselves which can continue to be used and developed following the conclusion of this work.

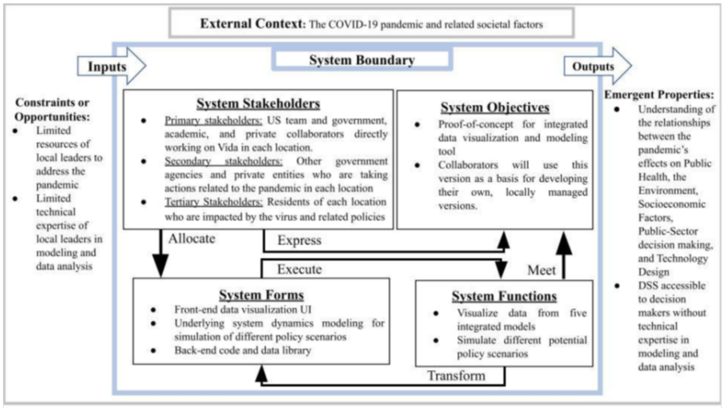

Figure 9: The high-level functional systems architecture of the Vida DSS.

2c. The evaluation process will test wether the collaborative SAF process for developing EVDT DSSs can fulfill its objectives, including (a) whether EVDT DSSs have the potential to improve the management of earth observation and socioeconomic data in a format usable by non-experts and (b) whether the collaborative SAF process is a practical and ethical improvement upon earlier technocratic methodologies.

3a & 3b. An outline of how to improve and expand the EVDT framework moving forward must be established. In the long run, EVDT is not intended to be an exclusive project of Space Enabled. Once EVDT has been refined and demonstrated through this and other projects, the next step will be to consolidate and standardize the underlying code, so as to facilitate furture improvements, as well as the reuse of materials for future contexts. The open source code repositories, already available online [153–155], will be used as a basis for building a community of practice, where individuals can contribute in a variety of ways, was discussed in Section 4.1.

Finally, outside the scope of the Deliverables, the overall process will advance the contribute to a variety of broader societal impacts. These include:

- Encourage the joint consideration of both human and environmental systems in a dynamic, continual fashion, thereby avoiding some of the negative consequences of siloed, static conservation mapping practices [33].
- Expand the population of EO data users by increasing accessibility and demonstrating utility of EO data to policymaking.
- Reduce burden of facilitation by space agencies. Many national space agencies are focused primarily on scientific missions. While they are often happy to assist other groups in using the data that their satellites generate, they often have limited resources and time to do so. For instance, the famous *Pale Blue Dot* photograph from taken by Voyager 1 after the conclusion of its primary mission, almost did not happen, as the photo had no scientific value and arranging for the shot required money and experts who had already been reassigned to other missions [183]. Integrated models could potentially enable the application organizations to be less reliant on direct assistance from space agencies, thereby freeing up space agency resources for other applications.

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