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Interactive Model for Assessing Mangrove Health, Ecosystem Services, Policy Consequences, and Satellite Design in Rio de Janeiro Using Earth Observation Data

Jack B. Reid[a] *, Danielle R. Wood[b]

[a] *Program in Media Arts and Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, USA, 02139,* `jackreid@mit.edu`
[b] *Program in Medias Arts and Sciences & Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, USA, 02139,* `drwood@media.mit.edu`
* Corresponding Author

There is an increasing need for tools to translate earth observation data into societally relevant metrics to inform human decision-making. To address this need, we present a multi-disciplinary, interactive modeling framework to advance ecological forecasting and policymaking using earth observation data. The Environment-Vulnerability-Decision-Technology (EVDT) Modeling Framework will integrate four models into one tool that can be adapted to specific applications; the four models address the following: earth science models of the Environment: Human Vulnerability and Societal Impact; Human Behavior and Decision-Making; and Technology Design for earth observation systems including satellites, airborne platforms and in-situ sensors 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. This paper presents a prototype that demonstrates the viability of the framework via a case study: the mangrove forests in the Guaratiba area of Rio de Janeiro. These mangroves are vulnerable due to urbanization and rising sea levels. They provide a variety of ecosystem services, including serving as a mechanism for carbon sequestration, supporting subsistence fishing, preventing coastal erosion, and attracting an ecotourism industry. The case study of mangrove and community health in Rio de Janeiro demonstrates all four model components. The Environment Model builds upon work by biospheric scientists Fatoyinbo and Lagomasino to use earth observation data, cloud computing, and machine learning to track mangrove extent, health, and vulnerability over time for a 600 km^2 area, as well as work by the ESPAÇO research group at the Federal University of Rio de Janeiro on the local mangrove ecosystem. To build the Human Vulnerability and Societal Impact Model, we are collaborating with ecosystem services economist Suhyun Jung to explain how policies impact mangrove health and how mangroves impact socioeconomic wellbeing. To create the Human Decision Making Model, we have partnered with the Pereira Passos Institute (the data science office of the Rio de Janeiro municipal government) to understand the policy history and socioeconomic factors. The Technology Model accounts for the types of data collection used by policy makers since 1975. Through such collaborations, we are able to build an integrated, interactive decision support tool that policymakers can use to assess mangrove health, ecosystem services value, and policy consequences. The model helps answer such questions as: (a) What is the state of the mangroves over time? (b) How are human communities impacting the mangroves? (c) what is the value of the mangrove ecosystem services to human communities? and (d) what policies can improve human and mangrove outcomes? This case study is demonstrative of the viability of a similar approach for ecosystems around the world.

Keywords: earth observation, model-based systems engineering, mangroves, machine learning, decision support

1. Introduction

There is an increasing need for tools to translate earth observation (EO) data into societally relevant metrics to inform human decision-making. This need is driven by the increasing socioeconomic and environmental consequences (positive and negative) of both human activities and technological development around the globe, as well as by an increasing (though still limited) awareness and understanding of such consequences. These consequences and possibilities of a brighter future are embedded in the United Nations (UN) Sustainable Development Goals (SDGs), which organize various areas of potential improvement, spanning economic development, environmental conservation and preservation, reduced inequalities, and more [1]. The SDG framework are no mere vague gestures of intention either. While they are not legally binding on any nations or other institutions, the 17 goals are broken down into 169 targets and 231 unique indicators that can be measured and progress charted. While significant gaps in our understanding and recognition of the connections between the environment, human wellbeing, technologies, and decision-making persist [2], the SDGs are a notable step towards acknowledging that our planet is one complex system and that, in many cases, attempts to tackle one domain without considering the others are fated to fail.

In parallel with this need for a multi-domain perspective, we have seen the rise of geospatial data more generally and EO data in particular. This has been partially driven by technological advances, such as the development and deployment of EO systems (both aerial and space-based) and advances in computation power. Another key component has been the democratization of access to such data and computational capabilities, as civil government satellite data has become largely freely available in the US and European union, limited data has been made available by other nations via international fora such as the Committee on Earth Observation Satellites (CEOS) and the Group of Earth Observations (GEO), and data processing and expertise have proliferated across the internet. Finally there has been a certain positive feedback between these dynamics. As awareness and knowledge of EO applications for sustainable development and disaster response have grown, so too has the interest in such applications, thereby driving further invention and creativity, both in the use of existing, largely scientific EO systems and in the development of new such systems. The rise of commercial EO system operators, such as Planet and Maxar, can thus been seen as both responding to and driving such application demand [3, 4]. This interest has also driven many fruitful institutional collaborations, such as that between GEO and the UN [5] and the more recent "Serving Society with Space Data" seminar series hosted by the Space Enabled Research Group and the Secure World Foundation [6].

Nonetheless, significant barriers remain to applying EO data for sustainable development. While data is more available than ever, it is not necessarily particularly accessible to many potential users. 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 EO systems are 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 [7], aquatic bacterial growths [8], or deforestation [9].

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. To this end, this paper expands and codifies a 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 [10]. Such a framework could also inform the development of future EO systems that are better designed for particular application contexts. In the beginning of the following section, this framework will be explained. The remainder of the paper will then focus on making the framework more tangible by examining a particular application in the city of Rio de Janeiro, Brazil, before concluding with remarks about the future of the framework and of the application case study.

It should also be noted that various parts of the primary application presented in this paper are still in progress, both in the sense that developing and applying this framework for the first time is a multi-year endeavour and in the sense that the coronavirus pandemic has adversely affected field visits, in-person interactions, and governmental priorities. That said, the currently state of the application is likely sufficient to demonstrate the EVDT Modeling Framework concept, with complete verification and validation to follow.

2. Materials and methods

This section presents the overall EVDT Modeling Framework, the circumstances surrounding the application case, the data and methods used in each component, and how these components are linked together. Each component of the EVDT Modeling Framework, as well as any application user interface, relies on different fields, methods, and theory. For sake of brevity, only those aspects thought to be necessary for understanding this paper and of primarily interest to this conference are included in this section.

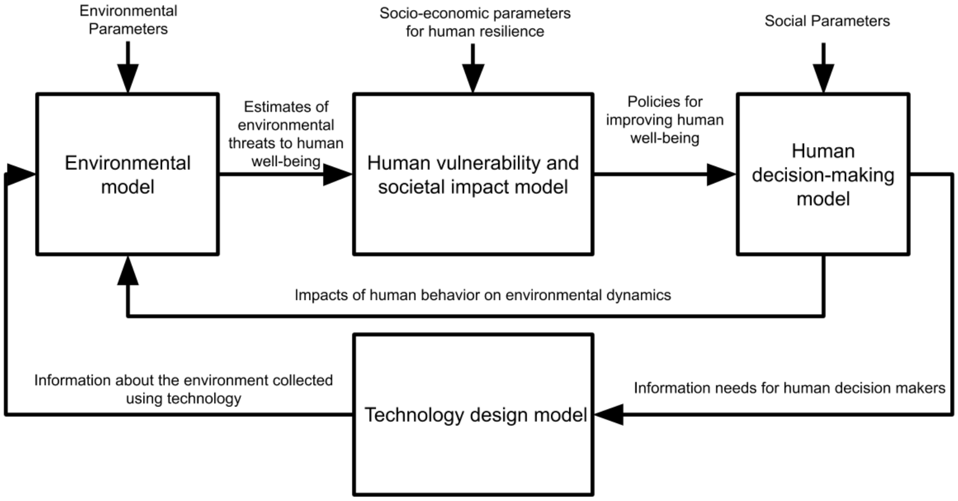

Fig. 1 Baseline version of the Environment - Vulnerability - Decision - Technology Model (Generic Case)

2.1. EVDT Modeling Framework

The EVDT Modeling Framework seeks to break down complex socio-environmental systems into four primary components, while still acknowledging and addressing the important linkages that exist between them, as seen in Figure 1. The Environment Model uses earth science methods to estimate the state of environmental phenomena; The Vulnerability Model captures societal impact of environmental changes including ecosystem services; the Decision Model captures human behavior and policy consequences; and the Technology Model provides tools to design earth observation systems or select among earth observation technologies such as satellites, airborne sensors, and in-situ sensors. This framework is targeted at responding to four questions, which can be specifically tailored to a particular application:

(a) The Environment Model asks, "What is happening in the natural environment?"
(b) The Vulnerability Model asks, "How will humans be impacted by what is happening in the natural environment?"
(c) The Decision Model asks, "What decisions are humans making in response to environmental factors and why?"
(d) The Technology Model asks, "What technology system can be designed or acquired to provide high quality information that supports human decision making?"

The first model, Environment, seeks to capture the history and behavior of the relevant natural phenomena to the application, such as weather patterns, plant growth, or ice formation, and thereby answer question (a). This is the component with the most robust literature and tools for the use of EO data, as many of these phenomena can and have been directly tracked from space-based EO systems for many years, though in many cases additional work is required to tune and calibrate such tools for a particular context.

This component directly feeds into the second model, Human Vulnerability and Societal Impact (hereafter referred to as merely as Vulnerability). This model seeks to capture and predict the degree of impact of some phenomena (usually environmental) on a set of people. Such impacts are most vividly seen in cases of natural disasters, but are certainly evident in countless other, less dramatic circumstances as well. It should be noted, as the name of this component seeks to imply, that these impacts need not be uniformly negative, but can also include positive consequences of natural phenomena with regards to income, health, or community.

The third model, Human Decision-Making, recognizes that humans are no mere passive recipients of external pressures, but also take action to shape and change our environments (here meaning both the nature, á la the Environment component, and their technologies, as will be discussed shortly). This decision-making takes place at a variety of scales, which will in turn determine the appropriate modeling method to pursue. Individual fishers may change their daily movement patterns in response to the availability of fish, or lack thereof, in such a way as to lend towards agent-based modeling (ABM). Governmental policy may have explicit rules on when the resources of a conservation site may be accessed, lending to a straightforward discrete-event simulation. In some cases, where the dynamics of human decision-making are too complicated to capture a priori, it may even make sense to have a human-in-the-loop as part of a more interactive simulation process.

The fourth and final model refers to Technology. Here we primarily refer to sensing technology, though we use this term broadly to refer to virtually any means of knowing the world, both the environment and society. This can rather straightforwardly refer to the design and development of a new space-based EO system, but might just as well include the deployment of in-situ measurement system, accessing existing data and integrating into the decision-making pipeline, or instituting a new data collection policy using already in-operation sensors. Numerous robust tools for designing and simulating EO system performance exist already, but, depending on the intended audience, some effort will often need to be taken to reduce the scope to focus on the most relevant components, such as the tradespace exploration process.

It should be noted that while we present a base EVDT Modeling Framework with these four components and the noted linkages, other components or additional linkages may be necessary in some contexts and the authors ourselves have done so in some other applications [11].

2.2. Study area: Guaratiba case study

The western coast of the Rio de Janeiro municipality, highlighted in Figure 2, is not as densely developed as the western urban core is (though this is rapidly changing). This coast includes numerous rural farms, fishing communities, and large industrial plants, the latter of which are primarily found in the northwest corner of the municipality. On the southern end of this coast is the Guaratiba area, which contains the largest remaining mangrove forest within the city of Rio de Janeiro, shown in Figure 3 . This forest is a sort of hub around which various land uses are arranged: 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 Guaratiba mangroves are vulnerable due to the aforementioned development according on their landward edge, which has been accelerated in recent years by the two megaevents that Rio de Janeiro has hosted within the past decade [12], as well as by rising sea levels on the seaward edge [13]. Numerous ecosystem services are provided by these mangroves, including highly efficient carbon sequestration, fishing and crab catching, coastal erosion prevention, and a local ecotourism industry [14]. These ecosystem services are often underappreciated by government planners, due both to their inherent quantification difficulty and due to the relatively unprivileged communities that they primarily accrue to. There is thus a need, on both the environmental and socioeconomic fronts, for the decision support provided by such a methodology as the proposed EVDT Modeling Framework. This suitability of this case study is further amplified by the fact that the Rio de Janeiro municipal government has long been committed to the collection and publishing of diverse datasets via their Data.Rio platform [15].

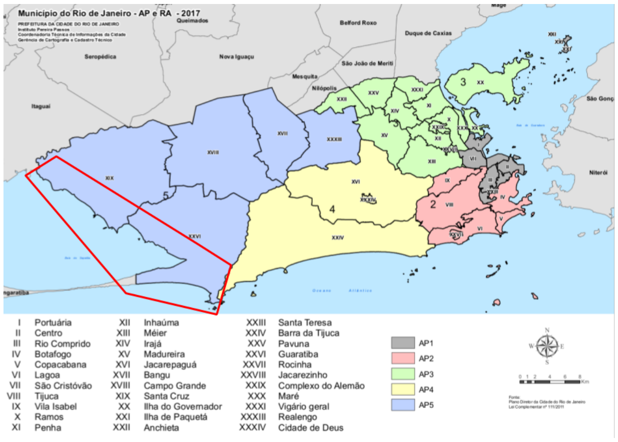

Fig. 2 Map of Rio de Janeiro with the area of interest indicated with the red boundary. The Guaratiba Administrative Region is labelled "XXVI"

In this case study context, the Environment Model primarily refers to the extent and health of the mangrove trees in the area. The Vulnerability Model refers to the various ecosystem services provided by these trees. This includes both global benefits such as carbon storage and local benefits such as food and other raw materials harvested from the forest and its associated waterways, as well as the impact of the mangrove presence on water quality and sewage removal for local inhabitants. The Decision-Making Model primarily refers to municipal-level government policymaking, particularly the urban zoning statues and the local conservation statuses and boundaries. Finally, the Technology Model refers to the access to various sensing technologies, including in-situ surveys, aerial surveys, and space-based EO systems. These considerations transform the four guiding questions, into more specific questions:

(a) **What is happening in the natural environment?** What are the impacts urban zoning and conservation policy on the mangrove forests? What role do complex secondary factors such as growth of informal settlements and the use of natural resources in and around the forest play?

(b) **How will humans be impacted by what is happening in the natural environment?** What impact does the designation of environmentally protected areas have on the community? What effects would the lack of mangroves have on the city? What is the value of the carbon sink of mangrove forests?

(c) **What decisions are humans making in response to environmental factors and why?** How are planning policies such as restricted land use conversion in certain protected natural reserves developed? How are other centralized and decentralized decisions made, such as the rate of urban expansion or the development of transportation infrastructure?

(d) **What technology system can be designed to provide high quality information that supports human decision making?** What satellite, aerial, and in-situ sensing platforms are needed by the Municipal System of Urban Information (SIURB) to accomplish their mission?

Fig. 3 Visual Landsat 8 OLI imagery of coastal Guaratiba. The red border indicates the general boundaries of the primary mangrove forest. Not all of the forest lies within the referenced biological reserve.

2.3. Environment Model

The Environment Model of this case study is predominantly interested in the health, the size (as measured by geographic extent), and height of the mangrove forest over time. Height of mangrove trees can be measured using aerial LIDAR [16] and Rio de Janeiro has recently conducted such a survey of the entire municipality, the data from which should be available shortly. This height can then be used to estimate biomass [17, 18], which is important for estimating the forests' carbon sequestration capabilities [9]. Historical height data can be estimated using space-based LIDAR and SAR data [19], though this method lacks the spatial resolution of aerial methods.

Regarding extent, several widely-used global mangrove extent maps have been generated, including by Giri [20], Spalding [21], and the Global Mangrove Watch (GMW) [22]. These are typically representative of specific years and, due to their global-scale, often have higher errors in specific localities, particularly involving the landward edge of mangrove forests and smaller copses of trees. In order to conduct extent-change tracking and to identify such copses, it is sometimes preferred to conduct more targeted estimations, as was done in this case. Mangrove extent was estimated using a Random Forest Classifier (100 trees, 8 variables per split) utilizing both single-band surface reflectance imagery and several multi-band indices from Landsat 7 ETM+, Landsat 8 OLI, Sentinel 2 MSI, and ALOS PALSAR. Training data was identified using a combination of Giri's 2000 map, GMW's 2015 map, and firsthand field visits. Planet Lab's PlanetScope surface reflectance imagery was also experimented with, but ultimately was determined to not provide sufficient identification improvements to warrant continued use. In order to eliminate false positives, a mask was used to filter out flagged pixels at over 40m in elevation, as determined by the Shuttle Radar Topography Mission (SRTM) dataset [23], and a kernel filter was used to eliminate solitary and near solitary pixels that were erroneously classified as mangroves. This classification, for the year 2018, can be seen in Figure 4. For a more detailed explanation of random forest classifier algorithms and their relevance to forest identification, see [24].

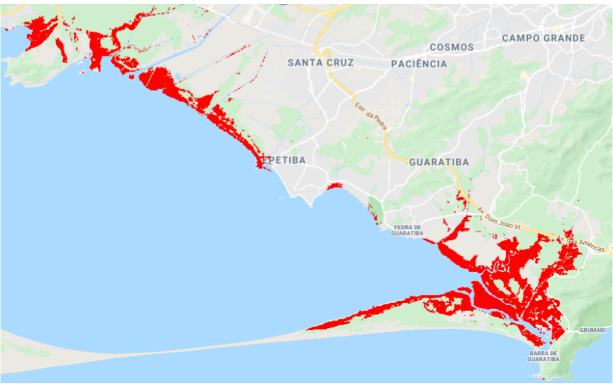

Fig. 4 Classification of mangrove extent in western Rio de Janeiro for the year 2018.

The Rio de Janeiro area contains three different species of mangroves, which makes exact identification and health tracking somewhat more difficult. Ultimately we elected to use the relatively simple and robust normalized difference vegetation index (NDVI), a normalized difference ratio of near infrared (NIR) and red surface reflectance, as seen in Equation 1. NDVI returns a value between -1 and 1, with 1 indicating a high likelihood of healthy vegetation, -1 indicating an absence of vegetation, and intermediate values indicating either possible vegetation or unhealthy vegetation, as seen in Figure 5. In Landsat 8's Operational Land Imager (OLI), the primary instrument used for tracking NDVI in this case study, the NIR band captures 0.845 µm to 0.885 µm light while the red band captures 0.630 µm to 0.680 µm light. Landsat 5 and 7 surface reflectance imagery were used as well, harmonized according to Roy et al. [25]. NDVI is the most commonly used surface reflectance index for tracking vegetation presence and health via remote observation [26, 27].

$$\text{NDVI} = \frac{NIR - Red}{NIR + Red} \tag{1}$$

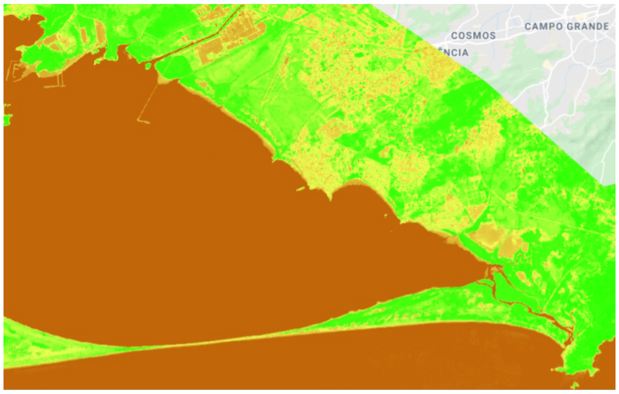

Fig. 5 False-Color image of area of interest showing an NDVI composite. The greenest pixels indicate healthy vegetation presence

In order to focus on significant, secular changes in mangrove health rather than cyclical or temporary changes, NDVI mean anomaly was used, rather than a straightforward NDVI time series. The equation for this can be seen in equation 2. Here $NDVI_{Ref}$ refers to the median NDVI value at a specific location (an individual pixel in this case) over a specified reference period. $NDVI_i$ refers to the NDVI value at that location for each of the images taken during the observation period, and n refers to the number of usable images (i.e. clear, no clouds, etc.) at a specific location. As mentioned earlier, NDVI is not a perfect measure of mangrove health in a multi-species ecosystem, but it is broadly accurate. With greater bands (more than 10) in the visual spectrum, it is possible to differentiate vegetation species in some cases, but free hyperspectral platforms have poor spatial resolutions that make them inadequate for this application [28].

$$Anomaly = \frac{\sum_{i=0}^{n}(NDVI_i - NDVI_{Ref})}{n} \tag{2}$$

The figures presented in this paper, such as Figure 6, used a reference period of August 31, 1999 to August 31, 2001 and an observation period was September 1, 2001 to September 1, 2018. It should be noted that mean anomaly is sensitive to the selection and duration of these periods, so the presented figures alone should not be taken as indicative of trends outside of the specified periods.

This EO data was accessed and proceed using Google Earth Engine (GEE), prior to being exported for use as part of the broader EVDT Modeling Framework. GEE is a free, cloud-based, geospatial programming platform that hosts free satellite imagery from a variety of sources. This platform obviates the need to download such imagery onto a computer for individual manual analysis. This method of extent and health tracking is largely based upon methods used by Lagomasino et al. [9]. Once this historical mangrove data has been processed, it serves as the foundation of estimating causal impacts between the EVDT components, as seen in Figure 7.

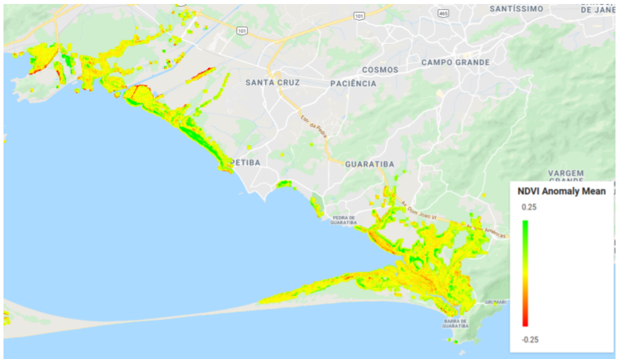

Fig. 6 False-Color image depicting NDVI mean anomaly. Green indicates new or healthier mangroves, red indicates reduction in extent or in health, yellow indicates no measured change.

2.4. *Vulnerability Model*

Various socioeconomic and demographic data, including employment rates and population density, was collected at several geographic scales, including bairros (neighborhoods), census blocks, and census microgrids. Much of this data was sourced from the national statistics agency, the Brazilian Institute of Geography and Statistics (IBGE). These were supplemented with municipally collected data, organized by the Pereira Passos Municipal Institute of Urbanism (IPP). Such data includes a UN-developed Multidimensional Poverty Index (IPM) [29], a municipally-customized social progress index [30], and detailed land use maps [31]. This data varies significantly in its geographic and temporal resolution. Additionally, as mentioned in Section 2.2, it is known that the local communities in the Guaratiba area benefit from various ecosystem services provided by the mangroves, but the exact forms these services take are unknown and their values have not been quantified. In order to better understand and quantify the dynamics linking mangrove health and conservation policies with local socioeconomic impact, the team is currently pursuing collaborating with an ecosystem services economist to analyze historical data and potentially to conduct household surveys. This historical data will be used in conjunction with the mangrove health history to estimate the "Carbon and Raw Material Impact" and "Local Socioeconomic Impact of Mangrove Loss," as shown in Figure 7. For more details on these types of methods, see [32, 33]. Once these historical dynamics are better understood, we can progress to predictive simulation of vulnerability.

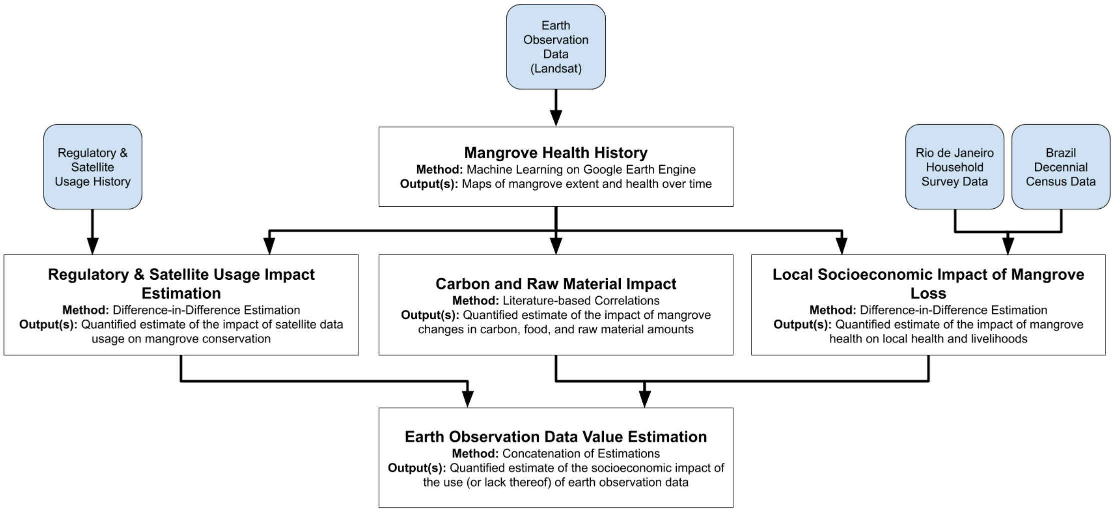

Fig. 7 Flowchart indicated various ways of estimating causal impact of one EVDT component on another

2.5. Human Behavior and Decision Making Model

Two primary policy decisions are current included in this EVDT application: conservation status and urban zoning. The histories of these are provided by the municipal Environmental Secretariat and Urban Planning Secretariat and accessed via the Data.Rio platform. The urban zoning categories are broadly similar to those in many cities around the world and include the types of commercial and industrial activity permitted and maximum floor area ratio allowed, among other factors. Conservation status, on the other hand, is somewhat complicated by the fact that, due to Rio de Janeiro's former status as the national capital of Brazil, the city was directly governed by the federal government for multiple centuries up until 1960. As a result, there are multiple conservation areas and other specialized jurisdictional areas in the Guaratiba area, both in close proximity and occasionally overlapping, governed by the municipal, state, and federal governments [34]. The relevant conservation areas in the area include:

- Área de Proteção Ambiental (APA) Ambiental das Brisas (municipal)
- APA da Orla da Baia de Sepetiba (municipal)
- Parque Natural Municipal da Serra da Capoeira Grande (municipal)
- Parque Nacional Municipal da Prainha (municipal)
- Parque Nacional Municipal de Grumari (municipal)
- Reserva Biológica e Arqueológica de Guaratiba (RBAG)* (state)
- APA Sepetiba II (state)
- Parque Estadual da Pedra Branca (state)

In these protected areas (which are classed as "integral protection"), little or no development and resource extraction is allowed. In addition to these areas (and often surround them), there are various municipally-defined "sustainable use" areas that allow for certain, restricted forms of development and resource extraction. There are also two different classes of boundary zones with fewer protections.

Additionally to these specifically environmental protections, there exists within the mangrove forest a federally-operated military base, CTEX, and several informal settlements, such as Araçatiba, situated on federal land but currently depending on the municipal government for formal recognition [36]. These areas hold their own (both *de facto* and *de jure*) environmental protections and risks.

The selection of these two axes of policy decisions (conservation status and urban zoning) was based on meetings and discussions with government officials from several municipal and federal agencies, university researchers, and local community members. Other axes were discussed and were of interest to particular audiences (such as transit network changes and conservation policy enforcement stringency), but these two held broad appeal and relative accessibility, while still having concrete historical data that are either quantitative or code-able qualitative. The history of these two policy axes over the past several decades will be used in conjunction with the Environment and Vulnerability Models to estimate the regulatory impact on these two domains, as shown in Figure 7.

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*Until 2006, this land was controlled by the nearby Brazillian Army Army Technology Center (CTEX), which continues to occupy a significant amount of land in the Guaratiba area and maintains some facilities within the RBAG. Similarly to other military administered lands in various parts of the world, CTEX's control of this land results in a kind of quasi-environmental protection that is simultaneously less formally determined than actual environmental conservation areas but much more stringently enforced in practice. For example, there is an army vehicle workshop that disposes of waste directly into the mangroves, but commercial activities and unauthorized human access are strictly forbidden [35]

2.6. Technology Design Model

In order to enable the estimation of the impact of EO data collection and use, as shown in the bottom box of Figure 7, the history of the collection and use of EO data (including both satellite and aerial platforms) was generated by the relevant municipal government agencies. Table 1 shows the simplified history of such use by the Urban Planning Secretariat of Rio de Janeiro. Not shown in this table is the geographic coverage of each product, the application that it was intended for, or the use of EO by other agencies. The 1975 product is currently in the process of being digitized and georeferenced, which is why a resolution is unknown at the moment.

Table 1 EO data use by the municipal Urban Planning Secretariat of Rio de Janeiro

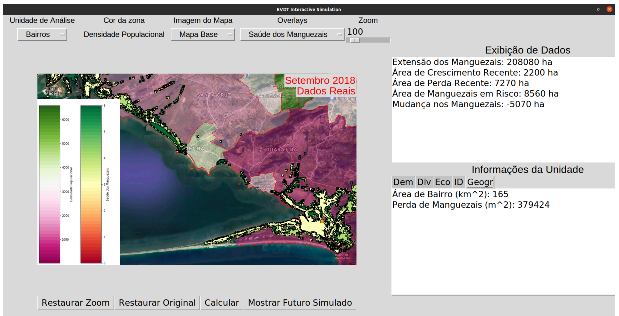
Year	Product	Platform
1975	Ortophoto	Aerial (???cm)
1999	Ortophoto	Analog camera (scanned to 85cm)
2004	Ortophoto	Analog camera (scanned to 50cm)
2006	Satellite imagery	Quickbird (60 cm)
2008	Satellite imagery	Quickbird (60 cm)
2009	Ortophoto	Digital camera (25 cm)
2010	Lidar survey	Aerial (10 pts/m2)
2010	Ortophoto	Digital camera (25 cm)
2011	Ortophoto	Digital camera (20 cm)
2012	Ortophoto	Digital camera (20 cm)
2013	Lidar survey	Aerial (2 pts/m2)
2013	Ortophoto	Digital camera (10 cm)
2015	Ortophoto	Digital camera (15 cm)
2016	Satellite imagery	Worldview 3 (30 cm)
2017	Satellite imagery	Worldview 2 (46 cm)
2018	Satellite imagery	Worldview 3 (32 cm)
2019	True Ortophoto	Digital camera (15 cm)
2019	Lidar survey	Aerial (8 pts/m2)

3. Results

At the time of writing, mangrove extent and health tracking has been completed; historical socioeconomic, demographic, policy, and EO data usage have been collected; and a user interface has been developed that incorporates this data. Environment and Vulnerability impact estimation and the development of a more robust Technology Design Model are ongoing.

3.1. Prototype user interface

A prototype user interface for the EVDT application has been developed and is being iteratively improved with consultation with the Rio de Janeiro collaborators and potential users. It is written in Python 3, can be run a standard personal computer, and utilizes shapefiles and CSVs as its primary forms of data input. Future versions that are hosted predominantly online and allow for the real-time importing of data are planned. A screen shot from the user interface can be seen in Figure 8. The image shown is in Portuguese, the primary language of the target audience, but multi-language functionality is currently being added and is in available in some other versions of the user interface, as seen in later figures. The user interface can present both historical data and simulated predictions in an interactive manner, enabling experimentation and learning. This user interface has two actionable units of analysis: the conservation areas and urban zones. In reality, both of these involve classification choices (is an area going to completely prohibit human use or be classed as 'for sustainable use only'?) and geographic choices (where exactly should the boundaries run). The current version only allows for classification choices within the range of currently used categories. The capability of generating new categories and geographic choices are being developed. Various other geographic units, such as bairros (neighborhoods) and census blocks, are accessible for presenting geographic data but are not themselves actionable units of analysis. This is necessary as various demographic and socioeconomic data likely to be relevant to decision-makers are only reported in particular geographic scales.



Cor da zona: Densidade Populacional

Setembro 2018
Dados Reais

Extensão dos Manguezais: 208080 ha
Área de Crescimento Recente: 2200 ha
Área de Perda Recente: 7270 ha
Área de Manguezais em Risco: 8560 ha
Mudança nos Manguezais: -5070 ha

Área de Bairro (km^2): 165
Perda de Manguezais (m^2): 379424

Fig. 8 Prototype user interface of the model, showing mangrove health, population density, and various other information for western Rio de Janeiro.

The mangrove extent and health data has been imported into the user interface from GEE and is visible both geographically (as a map overlay) and numerically (in the form of such values as the total mangrove extent area and the area of recent mangrove loss within the selected geographic unit of analysis). This enables the user to make concrete, quantitative comparisons in addition to visual comparisons. Other versions of the user interface can display temporal data represented as graphs, but users have found this more relevant in applications with dynamics acting on shorter time scales than the Guaratiba mangrove case, so it is not included here.

Fig. 9 Mangrove loss in two parts of the case study area. Lighter colored areas indicate less stringent environmental protections and darker colors indicate more stringent protected areas.

The user interface has been designed to focus on simplicity and modularity. Data is imported in the form of CSVs, shapefiles, and GeoTIFFs, all commonly used formats that do not require proprietary software. The program, which is written in the Python programming language, can be run on virtually any standard personal computer, including laptops, though simulation times may take several minutes depending on the exact specifications. Each component of the program is relatively discrete and adjustable without impacting other components. This includes both functional components such as data display versus simulation, and structural components, such as the four EVDT Models.

As stated earlier, most of the environmental and socioeconomic impact estimation work is ongoing, so the predictive simulation components of the program are largely placeholders that will be swapped out for more complete models in the future.

3.2. Intended Use and Outcomes

We can now return to the four guiding questions of the EVDT Modeling Framework, as applied to this case study in Section 2.2. Even it its rudimentary, in-progress form, the prototype EVDT model can provide some degree of insight on these questions, and to (a) in particular. As an example, Figure 9 shows screenshots from the user interface indicating areas of notable mangrove loss over the past twenty years in two different parts of the case study area. On the left is the Ilha de Maderia, in the northwest corner of Rio de Janeiro. Here, where the mangroves are either unprotected or inside an area designated "sustainable use," the mangrove loss is primarily on the landward facing edge of the forest, directly abutting recent industrial development. Meanwhile, in the southwest corner of the municipality, shown on the right in the same figure, the mangroves lie primarily in or along "integral protection" areas, and secondarily in "sustainable use" areas. In this area, the bulk of the mangrove loss is along the seaward edge. This suggests that conservation policy is at least correlated with different stressors on the forest. Additional, historical comparisons are being conducted to further identify the causal relationship and bring to light related factors.

There are multiple intended use audiences, including municipal government officials, local community leaders, and EO system designers. To ensure that the EVDT Model fulfills each of these communities needs, they are regular involved in the prototyping and requirement-setting process. A diagram depicting the objectives and user experience of one particular audience type is shown in Figure 10. Similar diagrams have been made for other audience types as well.

4. Discussion and future work

As is evident, work on both this application case study and on the EVDT Modeling Framework are far from complete. This paper has shown, however, that this multidisciplinary approach to using EO data for sustainable development decision-making is possible and worth pursuing further. In this section, we discuss the future work, both immediate and longer term, before moving onto the broader consequences of the EVDT Modeling Framework.

4.1. Immediate Additions and Expansions

The obvious next step is continue the socioeconomic impact assessment work and leverage this to developing robust simulations of future mangrove health and socioeconomic impact, as laid out in Figure 7. This will hopefully increase the policymakers' recognition of often underappreciated ecosystem services and provide local community members with an additional mechanism of advocacy. Another major component to be added is a fully fledged Technology Design component. In this case this will specifically entail tradespace exploration, where the users can assess different EO data products and their validity. Future variants of EVDT applications could even use simulated EO data to compare alternatives, not dissimilar to the Observing System Simulation Experiments (OSSEs) commonly used for meteorological and scientific satellite design. While the presented version focuses on the use of EO for assessing mangrove health, such data can be used to estimate other important factors in the Guaratiba case study, including water quality metrics such as turbidity and various socioeconomic factors, such as household income and building quality. Once these expansions and improvements have been integrated into the EVDT application, the intent is to move the user interface online to a cloud computing platform. This will both expand access and will facilitate various automated functions, such as the importing of updated data from the Data.Rio platform and integration with GEE, thereby allowing for more computational expensive calculations than are feasible on most personal computers.

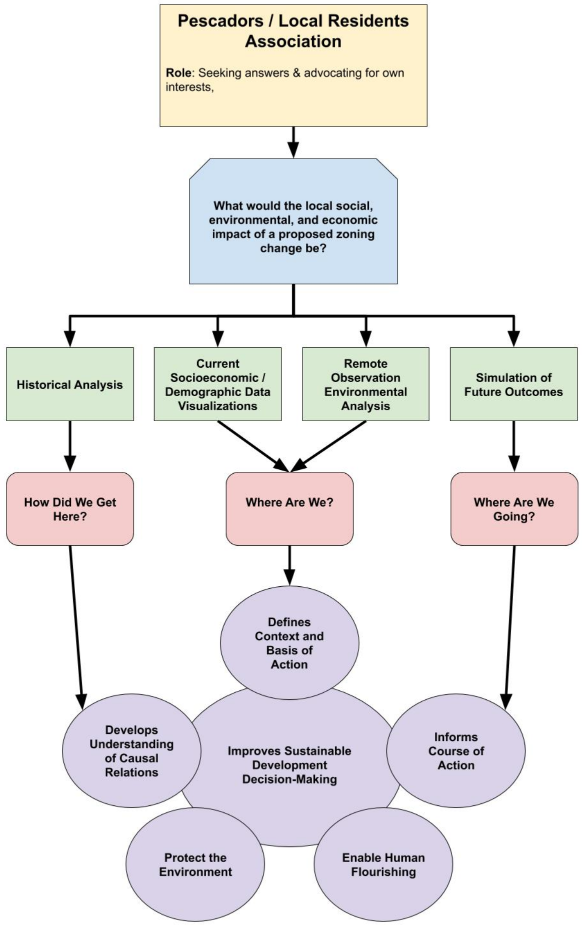


Fig. 10 Two potential user experience concepts for this case study.

4.2. *Verification and Validation*

For each component of EVDT, internal verification and validation work is required and is best conducted according to the norms and standards of that field. For the Environment Model in this 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. Olofsson et al. is an excellent reference for best practices of remote sensing accuracy assessments [37]. In general, any accuracy assessment needs to include proper sampling design, response design, and analysis. This in turn requires comparison of multiple data sources for agreement. As explained in Section 2.3, the current extent identification method already uses multiple EO satellite data sources. These can be individually compared for internal consistency, while the combined product can also be compared to the medium-resolution land use maps that are assembled by the Rio de Janeiro municipality every few years [31]. These maps themselves are based upon a variety of data sources, including commissioned satellite observations, aerial surveying, in-situ surveying techniques, and the maps from previous years. The NDVI tracking can also be compared to drone imagery, as the ESPAÇO research group periodically uses a Phantom DJI drone capable of both visual and near infrared imagery for aerial surveys of selective mangrove areas. For a more detailed explanation of such a validation methodology applied to water hyacinth, rather than mangroves, see [38, 39].

For verification and validation of the Vulnerability and Decision Models, in addition to various internal checks and comparisons of different Rio de Janeiro datasets, there is also the possibility of comparing the findings to one or more other municipalities. Several such municipalities, all located within the same state, contain significant mangrove forests and fishing communities, including Guapimirim, Magé, Itaguaí, Angra dos Reis, and Paraty. Each have their own conservation and urban development policies, as well as their own history of EO data use (or lack thereof, as the case may be). They may thus serve as a means of validating the causal relations identified by the ongoing work.

Once an internally validated EVDT model exists, user validation will be necessary to demonstrate the utility of framework in application. This validation will make use of the collection of methods known as purposeful gaming [40], wargaming [41–43], and role-playing gaming [44, 45]. Participants from various audience groups, such as the municipal Environmental Secretariat, local community members, and urban planning officials, will be recruited and asked to use the model to develop policies both individually and collaboratively. Through the use of comparison with other policymaking methods and of pre-and-post surveys, both the perceived and the assessed utility of the model can be assessed.

4.3. Longer Term Goals

In the further future, we envision using the results of the usability testing to further the development of interface standards for a more generalized integrated model framework. The various submodels used in the case studies may themselves be the first members of an openly accessible library of submodels. Potential user groups could adapt and reuse EVDT components in other applications, without having to start from scratch. In this way, a community of practice can be built over time, contributing to both the framework itself as well as to specific application models. Ultimately, the goal is for specific decision-maker organizations, either those involved with sustainable development or those involved with EO system design (or preferably the two of these together) to take ownership of development and operation of their own application models, rather than relying on primarily academic teams. Obviously this goal lies several years in the future, but it is hoped that the framework and case study as presented here represent first steps forward.

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