2014 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)
July 6-11, 2014, Beijing, China

Towards Data-Driven Environmental Planning and Policy Design – Leveraging Fuzzy Logic to Operationalize a Planning Framework

Amir Pourabdollah, Christian Wagner, Simon Miller, Michael Smith and Ken Wallace

***Abstract*— Environmental planning is complex, and requires careful consideration of a large number of factors, including quantitative ones (e.g., water balance) and qualitative ones (e.g., heterogeneous stakeholder input). To better integrate these factors, value-driven frameworks have been designed in the environmental conservation community. These frameworks are currently largely utilized manually by conservation and policy experts in order to inform policy design. In this paper, we present a fuzzy logic based system, which has been developed to operationalize the existing manual framework while preserving essential qualities, including the capture of uncertainty in the data sources and a consistent interpretability of the underlying automatic reasoning mechanisms. We provide a detailed description of the current implementation which can be applied in the operationalization of policy design and planning tasks in a range of natural resources management cases, followed by a set of concrete, practical outputs for a studied use case in Western Australia. Finally, we highlight remaining limitations and future work.**

I. Introduction

FUZZY Logic Systems (FLSs) have been widely used in dealing with uncertainty and imprecision in practical applications ranging from human resource allocation to stock market prediction and industrial control [1-3]. An area of FLS application is in environmental management and protection based on complex decision making processes under uncertain conditions, which encompass factors such as the delivery of human values and the associated management of a suite of abiotic (e.g., water) and biotic (e.g., communities of natural species) elements and key ecosystem processes.

More generally, effective environmental management is based on appropriate policy design and planning which in turn is based on the desired state of the environment as determined by one or more stakeholder groups such as local and federal government, residents, investors, conservationists, etc. The current state of the biotic elements and the associated processes (e.g., climate change) will also strongly influence system management. Significant amounts of work have been conducted in order to enable this "appropriate" design of policy and planning [4], with a key concept being the application of a top-down approach where initially stakeholder expectations are gathered in order to derive environmental management policies that support the realization of those expectations ([5-7]).

Amir Pourabdollah, Christian Wagner and Simon Miller are with the Horizon Digital Economy Research Institute of the University of Nottingham, Triumph Road, Nottingham NG7 2TU, UK, phone: +44 (0) 115 823 2554; fax: +44 (0) 115 823 2551; e-mail: amir.pourabdollah | christian.wagner | s.miller @ nottingham.ac.uk).

Michael Smith and Ken Wallace are with the Department of Parks and Wildlife, Government of Western Australia, 17 Dick Perry Avenue, Technology Park, Kensington, WA 6151, Australia, email: michael.smith | ken.wallace@dpaw.wa.gov.au

This work was supported by RCUK's Horizon Digital Economy Research Hub grant EP/G065802/1 and EPSRC grant EP/K012479/1.

In [6], a *values-driven* planning framework was introduced which formalizes the aforementioned approach as a well-defined sequence of steps. The work in [8], expanded on the first two steps of [6] to create five sub-steps, which are to:

1) Define a set of *values* for a given spatio-temporal conservation context.

2) Define an appropriate set of biotic *elements* that are applicable in the given context. A biotic element is typically a species or a community of species that can deliver value(s). Note that from hereafter, we simply use the word *element* to refer to biotic elements.

3) Rank or rate (from a stakeholder perspective) the importance of the given values arising from the set of given elements.

4) Estimate the provision of the values by individual *properties* of each element.

5) Estimate and compare the total value delivery generated by each element. This in turn enables elements to be ranked in order of their management priority.

For example, one desired value, "Productive Use", could be delivered by an element such as "Vegetation community". The ability of the element to deliver a value would depend on several properties (e.g., the species composition and structure of the community). The same element could also deliver multiple other values such as aesthetic pleasure, recreation, philosophical/spiritual contentment, etc.

Each of the steps listed above is tied to a series of conditions. For example, the value-set that drives the approach could be a comprehensive set that minimizes redundancies among the values. Significantly, all of the steps in the framework encompass potentially complex information and uncertainty, compounded by the reality that the required information must often be elicited from a variety of experts or expert/non-expert stakeholders. Such information is prone to imprecision, discord amongst contributors (inter-contributor uncertainty) and general uncertainty in terms of the individual responses (intra-contributor uncertainty).

In this paper, we describe the operationalization of the selected planning framework ([6]) based on a FLS. While aspects of the framework can be implemented using other artificial intelligence tools (e.g., Bayesian modeling), the proposed approach directly addresses perceived shortcomings, particularly in relation to the incorporation of known uncertainty aspects at various steps in the framework as well as preserving a maximal interpretability ("white-box-ness") of the resulting system.

We focus on steps 4 and 5 of the framework, showing how, for a given value-set, the actual value-delivery can be derived based on a set of elements which deliver said values through an underlying set of properties. We also show how the resulting system provides useful outputs, which can be directly employed to support planning policy decisions.

Section II provides background material on the formal (manual) framework, highlighting challenging aspects in terms of its operationalization (complexity and uncertainty), the applicable aspects of fuzzy systems as well as a brief overview of the resulting decision-making support tools. Section III describes the proposed system architecture, while Section IV provides detail on a current real world application. Finally, Section V provides conclusions, highlights remaining limitations and discusses the direction for future work.

II. BACKGROUND

In this section, we briefly introduce the environmental planning framework which is in place to support manual policy design and which is being operationalized through the system presented in the next sections. We then describe the practical challenges, output generation and suitability of fuzzy logic to the modelling of the framework.

A. *The Environmental Management Framework*

In the current context of general environmental change, well-defined and well-focused environmental management plans are crucial in order to maximize the positive contribution of available resources to the quality of human life, including the maximization of future options. Limited time, human resources, funding and equipment are pervasive problems in environmental management. As a consequence, natural resources conservation plans are necessarily focused on a limited set of environmental elements. In many cases, it is challenging to define an optimal set of elements for management priority [9].

In 2005, the World Health Organization (WHO) released the Millennium Ecosystem Assessment [10], a global set of guidelines for environmental decision-makers. In this document, the sustainable use of ecosystems and their contribution to human well-being is focused on as the center of environmental policy making [11]. Modern environmental planning frameworks such as the Value-Driven Framework in [6] follow this insight and thus focus on the preservation and enhancement of *human values*, i.e. those required for human survival and well-being, as the main management "drivers". The framework [6], which we are focusing on in this paper, further describes an evidence-driven method for the prioritization of conservation actions and elements in a given environment based on the delivery of the human values as perceived by stakeholders.

In this context, a stakeholder is anybody who has an interest in, is affected by, or can affect the given management plan [12]. Examples are representatives of conservation non-governmental organizations (NGOs), governmental agencies, educational bodies, farmers and residents. In the context of limited resources, conservation planning can thus be considered akin to an optimization problem where the resources are allocated in a way that maximizes satisfaction (across a heterogeneous group of stakeholders).

B. *From Framework to Operational System - Challenges*

The operational realization of a value-driven framework is highly challenging in a real world setting. Particular challenges are the complexity of natural resource environments, including the associated uncertainties in capturing environmental data; the difficulty of surveying stakeholders' opinions and finally the aggregation and evaluation of the resulting heterogeneous information. We explore some of these aspects below.

1. *System complexity:* Managing the interwoven many-to-many relationships and interactions in an ecosystem is a complex problem with large numbers of inputs and outputs. Simultaneously, it has been shown that complex management tools are likely to be rejected by stakeholders [13]. Limiting and precisely defining a number of inputs and outputs can reduce the complexity of modeling such a multifaceted phenomenon. One way of achieving this is to have a well-focused and clear value delivery analysis in conjunction with a specific management framework.

2. *Uncertainty:* The data required for decision-making includes information collected about the environment using a variety of different methods. These methods entail many sources of epistemic and linguistic uncertainty [14]. For example, the number of a particular species, size of a vegetation community or the intactness of a waterbird community are rarely known precisely. Even sensor-based information, such as groundwater salinity levels, is subject to measurement uncertainties.

A well-known study on the different types of uncertainties involved in ecological systems is conducted in [15]. Here, the sources of uncertainties are summarized/categorized as "knowing too little", "knowing too differently" and "accepting not to know". For example, consider measuring the composition of different elements. An estimate of abundance will almost certainly contain a considerable measurement uncertainty, as formulated in [16]. This is a case of "knowing too little" as well as "accepting not to know". In a studied region in Southern Africa [16], about 50% measurement variance is calculated, which could be reduced by limiting the study's space-time context. Another source of uncertainty is that the same measurement is made using different methods, which may lead to different results ("knowing too differently").

3. *Stakeholders*: Most environmental decisions are made without detailed data. In these situations, modeling environmental interactions is not practicable without eliciting expert opinion from stakeholders including local conservation and industry groups, professional scientists and natural resource managers. Stakeholders and experts differ in motivation and level of knowledge/experience leading to inter-expert uncertainty (multiple experts provide different data). Finally, even a single expert may

come up with different results at different times (intra-expert uncertainty). Thus, effective expert knowledge elicitation and application is a significant challenge [17].

C. Generating Outputs – Policy Design Support

In the context of environmental management, decisions are difficult to make because of the imprecise nature of ecosystems [18]. Environmental Decision-Support Systems (EDSSs) [19] are developed based on a number of techniques including artificial intelligence, stakeholder participation, statistical/numerical methods and geographical information systems [20, 21]. Within the described value-driven framework, the human values are the drivers of the planning process. Thus, in order to operationalize the framework, the EDSS-specific outputs are designed to indicate (to decision makers) the optimized resource management for the maximum value delivery in a given setting. We will be supporting the policy-making process by focusing on the generation of the following three key outputs:

1. *Value Delivery Report:* An estimate of the delivered human values based on the modeled environment is the primary output. This shows how much of each human value is delivered/produced based on data derived from direct measurement and expert input.

2. *Prioritized Conservation List:* A list of the natural resource elements ranked by their value delivery. This provides policy makers with a basis for ranking elements for subsequent planning. An EDSS example that has utilized different technologies to prioritize a list of elements for conservation in the Mississippi River is presented in [22]. However, it does not use human value delivery as the basis for priority setting.

3. *Sensitivity Analysis:* A sensitivity analysis, i.e. an analysis of the amount of change in outputs due to a given change in input parameters, which is a common method in analyzing environmental models with uncertainties [23]. In the case of designing environmental policy, when the value delivery contribution of each element is known, it is crucial to know the variation of the value delivery with respect to the changes in each input parameter. This analysis shows the policy designers how stable the system is as well as how the results change in response to small or large input changes. EDSS can also contain some other common analysis tools e.g., risk and benefit-cost analysis, which are also part of our current research project but which we will not focus on further as part of this paper.

D. Fuzzy Logic Based Modeling

Since its introduction in 1965 [24], fuzzy sets have been widely used for modeling and analyzing real world systems when complexity, uncertainty and vagueness are involved.

Fuzzy logic systematically deals with decision-making problems in uncertain and complex systems [25, 26], so the challenges outlined above make fuzzy logic a suitable modeling approach for environmental management [18]. As an example, fuzzy logic is particularly useful in finding intermediate solutions where the different stakeholders have some interest conflicts – e.g., the possible conflicts between the recreation and philosophical/spiritual contentment values [27].

We briefly review a number of works applying fuzzy logic based modeling in environmental management and associated decision making support, however the approach taken in this paper differs in that it applies a value-driven framework. In [28], fuzzy sets are used to support decision-making in the context of air pollution. While fuzzy sets are used to handle the environmental facts, no fuzzy logic system is employed. Similarly in [29], environmental facts are represented as fuzzy sets in order to classify and quantify environmental facts, as well as dealing with uncertain or missing data. The work in [30] reviews rule-based fuzzy logic modeling of environmental facts. The application of FLSs in classification of species is also presented in [31] which could be used towards the definition of elements in the value driven framework discussed here.

Further, there are studies considering the incorporation of fuzziness into geographical contexts of environmental management. A fuzzy logic based model of geographical extents of vegetation using remotely-sensed imagery has been considered in [32]. Finally, a fuzzy logic based approach for wetlands classification is provided in [18]. The key differences between these works and our approach lie in the underlying environmental management framework (i.e. the data sources and types employed) and its operationalization.

III. SYSTEM ARCHITECTURE

In order to operationalize the value-driven framework and consequently provide EDSS tools for policy-makers, we use a FLS to structure a computational model for steps 4 and 5 defined in Section 1 (i.e. estimating the human value delivery for given elements). In other words, the aim is to first quantify *value delivery* by the *elements* (given their individual *properties*) through a FLS and second, to further process and interpret the FLS's outputs.

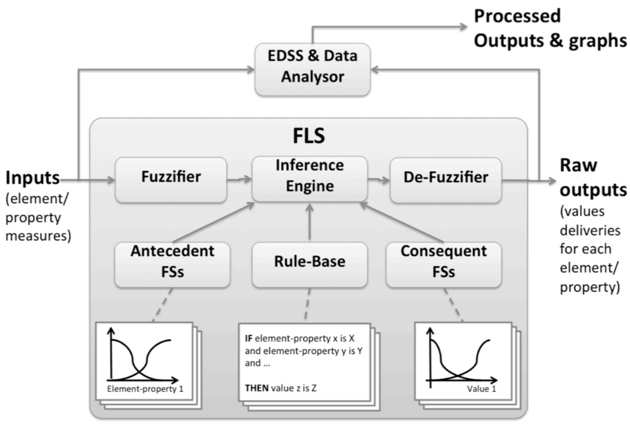


Figure 1: The system architecture

An overview of the system structure is shown in Fig. 1. Briefly, the FLS processes the inputs (element property measurements/assessments) and produces raw outputs (value deliveries from elements). The raw outputs together with the inputs are processed to produce the EDSS-specific results. The details of the system development are described in the following sub-sections.

A. System Setup

As for every FLS, the basic information required during its design stage relates to the basic parameters (e.g., number of inputs/outputs), the fuzzy sets (FSs) and the fuzzy rules capturing the relationship between inputs and outputs. In order to elucidate the information required to define the basic parameters, the following steps described in the value-driven framework [6] are followed. (In practice, they are completed by the environmental policy makers, experts and/or by surveying the stakeholders.)

1. Defining a concise vector of V human *values* (e.g., productive use, recreation, etc.) that are important to be delivered, each one in the range of [0,1], where 1 refers to the full value delivery and 0 refers to no value delivery. Each value is denoted as v_i $(1 \leq i \leq V)$.

2. Defining a vector of E *elements* (e.g., riparian vegetation, waterbirds, etc.) that exist in the conservation context and that may be related to the delivery of the human values defined in Step 1. Each element is denoted as e_j $(1 \leq j \leq E)$.

3. Finally, each element is described through a vector of measureable properties (e.g., the *area* of the riparian vegetation) for each element. If element j has P_j properties, we define:

$$p_{j,k} = \text{the } k\text{th property of element } j, \quad \text{where } 1 \leq j \leq E \text{ and } 1 \leq k \leq P_j. \qquad (1)$$

Hereafter, we use indices *i, j* and *k* for values, elements and properties respectively. In our case for simplicity, all elements have the same number of *P=4* properties (namely: *natural species richness, intactness, rarity,* and *size*). The range and the unit of each property are also defined (e.g., minimum/maximum possible size in the given context). For example, the vectors of values, elements and properties are respectively defined as:

Values: (v_1 =*knowledg and education*, v_2 =*productive use*, …, v_V);
Elements: (e_1 = *waterbirds*, e_2 = *mamals*, …, e_E);
Properties: ($p_{1,1}$ = *richness of waterbirds*, $p_{1,2}$ = *intactness of waterbirds*, … , $p_{2,1}$ = *richness of mammals*, …, $p_{E,P}$)

In order to capture the value delivery (i.e., the output) within the FLS, we define a number of consequent FSs for each value in order to capture the magnitude of value delivery (e.g. *high, moderate, low*). For each consequent FS, a membership function (MF) is defined by an expert or a group of experts. Currently, the MFs are simply chosen to evenly cover the universe of discourse. Fig. 2 shows an example of multiple FSs for a single value.

In order to define the antecedents, it is important to consider that it is the properties of a given element that define how well said element can deliver a given value. For example, when compared to other elements in the management area, if the *species richness* (property) of the *waterbird population* (element) is low, then, its ability to contribute to the delivery of the value *aesthetic pleasure* is low. Thus, the antecedent of the FLS is constructed from the properties of all elements. Each property (and its level of presence or magnitude in the environment) is described by a number of FSs. Fig. 3 provides an example of the three FSs defining the levels of the property *intactness* of the element *amphibians*.

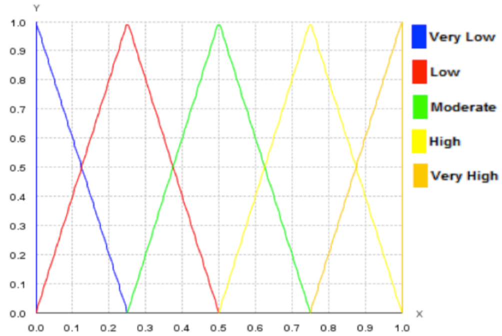


Figure 2: Sample consequence FSs for a single value (Productive Use).

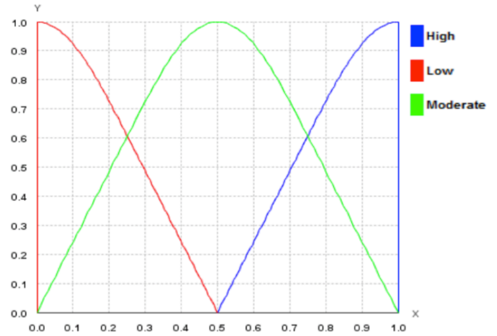


Figure 3: Sample antecedent FSs for a single property (Amphibians).

For simplicity, in the current iteration of the work and in this paper, it is assumed that all the properties for all elements are described by the same number of FSs, namely: three. The actual types of antecedent and consequent FSs are chosen by the system user at design time from a choice of triangular, trapezoidal or Gaussian as further detailed in Section IV. In the future, more complex designs for the fuzzy sets, such as data-driven approaches, could be adopted.

The next step is the construction of the rule-base, i.e. the set of fuzzy rules which follow the same form as the following example:

IF richness_of_waterbirds IS low AND
intactness_of_waterbirds IS low AND …
THEN ValueDelivery_of_AestheticJoy IS low

Note that currently the AND logical connective is used throughout (implemented as the minimum t-norm in the system). The actual rule-base is constructed by experts or stakeholders in a purpose built process which we will describe in detail as part of a future publication.

B. Fuzzy Logic System Execution

In the resulting FLS, singleton fuzzifier, centroid de-fuzzifier and Mamdani inference are used [33], while minimum and maximum are employed for the t-norm and t-conorm operators respectively.

The FLS's numerical inputs are elicited or collected from experts based on data collected in the respective conservation context (ranging from species diversity assessments to local measurements such as salinity assessments), for all the element/property combinations. Each input is then converted into a singleton FS. The pre-defined rule-base is employed to derive the specific output FSs, one for each element-property-value combination. By applying de-fuzzification, the centroid of each output FS is calculated, indicating how much of a given value is delivered by the individual elements through any of their given properties.

Formally, if $p_{j,k}$ is defined in (1), *each* FLS individual output is a number in the range of [0,1]) denoted as:

$$d^{i}_{j,k} = \text{the } i^{th} \text{ value delivery caused by input } p_{j,k} \quad \text{where } 1 \le i \le V, 1 \le j \le E, 1 \le k \le P \tag{2}$$

In each execution, the FLS takes the properties vector (defined in (1)) as the input and returns a number of outputs in the form of (2).

C. Data Analysis and Decision Support

The inputs and outputs of the described FLS are leveraged to realize the described EDSS reports outlined in Section II.C. Specifically, the following three EDSS outputs are derived from a *single FLS execution*, i.e. a static context based on a single set of inputs.

1) *Value Delivery Contribution per Element for a Given Value:* A primary EDSS report is made where *the outputs* defined in (2) are averaged over all the properties of each element. The result is a set of normalized numbers where each one is defined as:

$$s(i,j) = \frac{\sum_{k=1}^{P} d^{i}_{j,k}}{V};\ 1 \le i \le V, 1 \le j \le E \tag{3}$$

Each $s\,(i,j)$ shows the averaged contribution of the *j*th element towards the delivery of the *i*th value.

2) *Value Delivery per Element across all Values:* If all the calculated $s(i,j)$s in (3) are averaged again over all the values, a set of normalized numbers are generated where each one is defined as:

$$s'(j) = \frac{\sum_{i=1}^{V} s(i,j)}{V};\ 1 \le j \le E \tag{4}$$

Each $s'(j)$ is the averaged contributions of the *j*th element towards the delivery of *all* the values. A table of sorted $s'(j)$s for all elements makes an important EDSS report which is the prioritized list of elements –to be conserved- along with their value delivery contributions.

3) *Value Delivery across all Elements:* If the calculated $s(i,j)$s in (3) are averaged over all the elements the resulting normalized numbers are in the form of:

$$s''(i) = \frac{\sum_{j=1}^{E} s(i,j)}{E} \mid 1 \le\ i \le V\} \tag{5}$$

$s''(i)$ is the averaged delivery of the *i*th value across all the elements, which makes another EDSS report when calculated for all the values.

Further, a *dynamic data analysis* is conducted where the FLS inputs are perturbed in order to capture changes in value delivery in relation to input changes. This enables the following EDSS outputs:

1) *Sensitivity Analysis of Elements' Relative Values*: It is useful to know how the total value delivery changes if a particular property of an element changes around its actual measure. As an example, one may need to know how the delivery of all values are affected if the area of a vegetation community is slightly reduced. Having a particular element/property (j and k), different $p_{j,k}$ s (defined in (1)) are automatically produced in a particular range around the initial measure and are repeatedly fed into the FLS. Each FLS execution results in a tuple in the form of $(p_{j,k}, s'(j))$ where $s'(j)$ is defined in (4). The tuples from all the FLS "runs" represent a 2-D graph, as exemplified in Fig. 4a. The shape of the graph captures the sensitivity of the overall value delivery around the initial measure of a single property.

2) *Sensitivity Analysis of Value Delivery:* It is also useful to consider the sensitivity of a single value delivery when a particular property changes. We notice that a single property cannot exactly change across all the elements, since each one may have a different context, range and unit. For example, the property *size* in reality does not equally increase for a vegetation element and a water bird element. However since we assume that all the elements have the same set of properties, it is possible to change a given property by a given percentage for all elements. For example, the sensitivity of value *productive use* is considered when the size of all the elements are increased by 5%. Repeated FLS executions fed by the different inputs produce a graph exemplified in Fig. 4b, which shows the sensitivity of the i*th* value delivery when the *k*th property changes around its initial measure.

3) *Control Surface*: A three-dimensional control surface is another type of EDSS output that is available and has been found a useful EDSS output. Such a 3-D visualization helps policy-makers understand the stability of a certain value delivery according to the variation of two input parameters. In particular, it is interesting to study the changes in a value delivery if two properties of a single element simultaneously change. The currently implemented control surface graph takes two particular properties of a single element (along *x* and *y*-axis) and the delivery of a single value (along *z*-axis). An example of this is given in Fig. 4c.

D. User-Interfacing and Software Platform

A web-based user-interface has been developed in order to make the EDSS accessible to both expert and non-expert users in multiple locations. This is of particular importance in order to make the system accessible beyond computer science, namely to all stakeholders from modeling experts to local environmental management experts and policy makers. In the current iteration of the system, the following information can be provided/altered by the user:

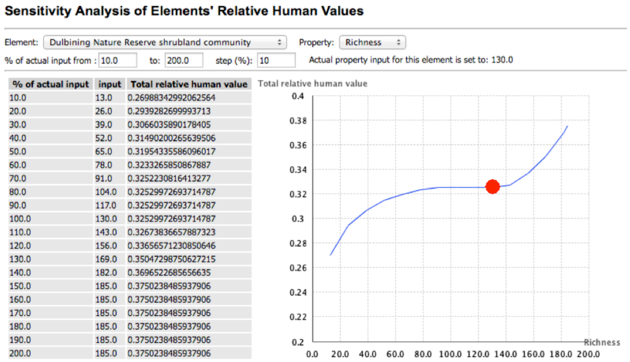
1) *Values and their FSs:* For each FS, the type (a choice of triangular, trapezoidal or Gaussian) and the associated parameters to each type are set via a graphical interface.

2) *Elements, properties and their FSs:* FSs for each property are managed similar to the value FSs. At the

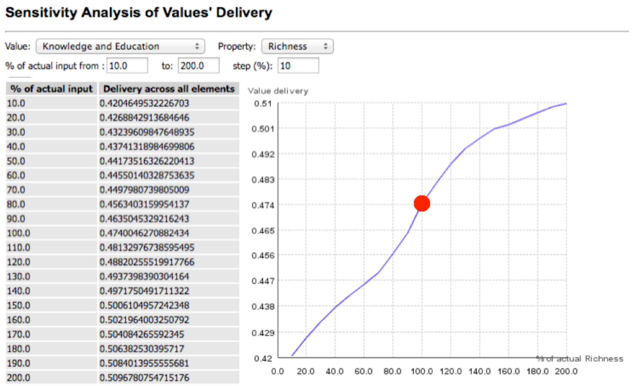
same time, the user enters the measurement of each property of each element.

3) *Rule-base:* For each rule, the antecedent(s) and the consequence are taken from the expert user.

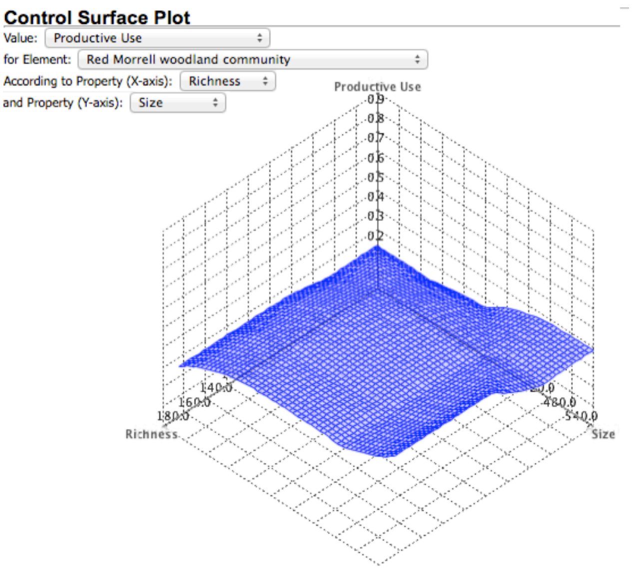
The overall system is running on cloud infrastructure, making it accessible on demand, world-wide, for any number of conservation contexts. For a given context, the FSs, MFs and inputs are stored in a central database.



(a)



(b)



(c)

Figure 4: A sample of sensitivity analysis graphs: (a) the sensitivity of the total value delivery with respect to a single element/property changes. The red dot indicates the actual richness. (b) The sensitivity of value deliveries to a single property change among all elements. (c) A sample control surface: This visualizes the sensitivity of a single value delivery (Productive Use) with respect to the changes in two properties (Size and Richness) of an element (Red Morell Woodland Community).

The technologies used in the system development are:

- Juzzy, an open-source Java library for fuzzy logic computing [34]
- Apache Tomcat™ for Java Web Serving
- PostgreSQL® for database management
- Qercus for database interfacing; and
- Windows Azure™ for the cloud Web hosting.

IV. REAL-WORLD APPLICATION

While the previous section formally described the system architecture, in this section we show its practical application in an ongoing environmental planning context. To demonstrate the system, real world data gathered from a planning task in Toolibin Lake Natural Diversity Recovery Catchment in Western Australia [35] is used [8]. The Toolibin Lake Natural Diversity Recovery Catchment is the focus of conservation planning because it includes a series of regionally significant biological communities and species that are under threat from a range of different processes [35].

A. System Setup

Following the framework in [6], in order to provide direction for planning and management, a concise list of values was developed and ranked by a group of stakeholder representatives. From the ranking exercise, three priority values were identified to be delivered by the biological elements: *knowledge, heritage and education, productive use* and *philosophical/spiritual contentment*. Each value has five triangular symmetric FSs (called *very low, low, moderate, high* and *very high*).

Working with a small group of experts, 22 elements were defined (listed in the next sub-section). Four measurable properties (*natural species richness, intactness, rarity,* and *size*) were identified as important for each element in terms of delivering values. All properties and their relationships with the values are defined and conceptualized in [8]. We note that here we do not discuss the selection of elements and values further but focus on demonstrating the generation of EDSS outputs by the proposed system.

The designed list of values, elements and properties are entered into the system. The designed FSs for each value and for each element-property combination are entered independently via the browser-based user interface. Each of element-property combinations (22 elements having 3 properties lead to 88 combinations) has three FSs called *high*, *low* and *moderate* (see example in Fig. 3) as well as its own range and input measure. The FSs can also be interactively altered using a browser-based user interface.

B. Rule-base Development

A team of conservation experts applied the following approach to establish the rule-base: First every possible combination of properties was associated with all individual three values, resulting in 243 rules (34 combinations for antecedents and 3 possible consequents). Where a particular property set was low, moderate or high it received a particular score towards delivering a particular value (e.g. for philosophical/spiritual contentment value, the scores are 1 for low, 2 for moderate and 3 for high).

antecedant	consequence
Intactness is **Low** Rarity is **Low** Richness is **Low** Size is **Low**	Knowledge and Education is **Very Low**
Intactness is **Low** Rarity is **Moderate** Richness is **Low** Size is **Low**	Knowledge and Education is **Low**
Intactness is **Low** Rarity is **High** Richness is **Low** Size is **Low**	Knowledge and Education is **Low**

•••

Figure 5: The user interface for editing the rule-base.

The resulting score for each combination was calculated by summing the individual property scores (e.g., rarity is low (1) + richness is low (1) + intactness is moderate (2) + size is large (3) = 7). In order to define the consequent of each rule, the resulting score calculated for each antecedent is considered, e.g., if the score is 4 to 5 then the philosophical/spiritual contentment delivery is very low, for 6-7 it is moderate and for 10-11 it is very high. The expert users can manually edit the rule-base (Fig. 5).

While the above provides a rapid way to define the rule-base, clear shortcomings include potential oversimplification and omission of details. In the future, we are considering other approaches such as crowd-sourcing and the establishment of a system for incremental rule-base construction over time.

C. *The System Reports*

The system provides a number of key outputs. The various forms of sensitivity analyses (e.g., Fig. 4) are used to provide a visual representation of the model outputs for experts and stakeholders. For example, in Fig. 4a the sensitivity of the overall value delivery to the variation of the richness in the Dulbining Nature Reserve shrubland community is shown. Also in Fig. 4b for instance, the sensitivity of the *knowledge and education*'s value delivery to changes in the *richness* of all elements is illustrated. This shows a relative stability of the value delivery for the actual current (red dot) richness levels which is unlikely to suffer from minor decreases in richness. An example of control surface (Fig. 4c) shows the sensitivity of the productive use value based on the changes in size and richness of Red Morrell woodland community. The predicted delivery of the values, by each of the elements can be presented as centroid estimates. This will allow the priority elements to be identified.

The detailed value delivery results (Fig. 6) are tables showing the two discussed EDSS reports in section III.C: The sorted value deliveries across all elements (2) and the elements' relative value across all elements (3). For example, according to the top table shown in Fig. 6 the delivery of philosophical/spiritual contentment is the highest contribution. The lower table in Fig. 6, is a prioritized list that ranks the elements according to their value delivery contributions that ultimately shows their conservation importance to the policy makers.

Importantly, the outputs from the sensitivity analyses can be used to develop functions that express the relationships between particular properties of elements and the related utility on an element-by-element basis.

Value Delivery Results

Value delivery across all elements - sorted

Name	Delivery
Philosophical/Spiritual/Intrinsic	0.462944605413505
Knowledge and Education	0.3311565380021563
Productive Use	0.3072082166694062

Elements' relative human value across all values - sorted

Name	Relative human value
Dulbining Nature Reserve woodland community	0.48748281759878664
Waterbirds	0.47451031977378233
Toolibin Lake Vegetation community	0.4721186367963366
Aquatic Invertebrate Community	0.46718086913665485
Dingerlin Well Nature Reserve shrubland community	0.46089160897677955
Resident terrestrial birds	0.4546306602534958
Mammals	0.4504797051976033
Dulbining Wetland (2) vegetation community	0.4153056872578283
Walbyring Lake vegetation community	0.403473525701828

•••

Figure 6: The value delivery report

This information is critical to conducting benefit-cost analyses where the benefits are expressed in terms of the utility expected as a consequence of a change in an element property in response to a specific management strategy.

V. Conclusion and Future Works

In this paper, we highlighted the challenging domain of environmental policy design, in particular in relation to the incorporation of a large number of heterogeneous and uncertain information sources that together are employed to guide and inform conservation policy decision making. We have presented a fuzzy logic based approach for operationalizing an established (but so-far only manually applied) value-driven, environmental conservation framework. The complex and uncertain nature of relevant variables in the challenging area of environmental conservation makes fuzzy logic a highly suitable modeling approach.

In particular, we have highlighted the role of the FLS within the overall system and have showcased how the complete system has been developed into an online, interactive, cloud-based conservation-support tool, which is currently being employed and evaluated (to inform future development) by the Western Australian Department for Parks and Wildlife. We have shown a selection of outputs of the system for a conservation area in Western Australia for which environmental conservation planning is currently under way. This is the only developed FLS based on the framework described in [6] so the results, their practicality and usefulness are being evaluated by the local environmental experts. Our early results and feedbacks from stakeholders have highlighted the capability of fuzzy sets to capture this uncertainty as well as the high interpretability of the resulting system as key strong points of the fuzzy logic based approach.

While the proposed FLS enables the uncertainty capture within the system, we are currently focusing on expanding the work in two main areas. First, while the employed singleton fuzzifier is computationally attractive, it is expected that employing a non-singleton fuzzifier will enable the capture of the actual uncertainty in the property assessments, which are frequently uncertain and/or noisy (e.g., population size is usually determined through species count exercises which strongly depend on time of year, chosen quadrat, sampling frequency, etc.).

More recently, an increasing interest in type-2 FLSs [36] has focused on the conceptualization of, and computation with human-sourced information based on/around human language, e.g., Computing with Words [37] and the modeling of concepts such as agreement across multiple sources [38]. An example here is the capture of the stakeholders' agreement, as analyzed in [39]. Thus the second direction for future works is employing type-2 sets and their additional degrees of freedom [40] that may provide a promising development area in order to accurately capture the uncertainties present, in particular without increasing the complexity at the rule base level.

ACKNOWLEDGMENT

We would like to thank Ronan O'Brien who helped in the rule base creation. We would also like to thank the anonymous experts for their contributions to the approach. This work was partially supported by the RCUK Horizon Digital Economy Research Hub grant EP/G065802/1 and the EPSRC grant EP/K012479/1.

REFERENCES

[1] A. Bárdossy and L. Duckstein, "Fuzzy rule-based modeling with applications to geophysical, biological, and engineering systems," ed: CRC Press, 1995.

[2] G. Bojadziev and M. Bojadziev, *Fuzzy logic for business, finance, and management*: World Scientific Publishing Co., Inc., 2007.

[3] J. Yen, R. Langari, and L. A. Zadeh, *Industrial applications of fuzzy logic and intelligent systems*: IEEE Press, 1995.

[4] R. Gregory, L. Failing, M. Harstone, G. Long, T. McDaniels, and D. Ohlson, *Structured decision making: a practical guide to environmental management choices*: John Wiley & Sons, 2012.

[5] K. J. Wallace, "Classification of ecosystem services: problems and solutions," *Biological conservation,* vol. 139, pp. 235-246, 2007.

[6] K. J. Wallace, "Values: drivers for planning biodiversity management," *Environmental Science & Policy,* vol. 17, pp. 1-11, 2012.

[7] J. P. Reser and J. M. Bentrupperbäumer, "What and where are environmental values? Assessing the impacts of current diversity of use of 'environmental'and 'World Heritage'values," *Journal of Environmental Psychology,* vol. 25, pp. 125-146, 2005.

[8] M. J. Smith, K. J. Wallace, and C. Wagner, "Using properties to rate biological elements on their delivery of human values," *Ecology and Society,* In review.

[9] D. Lindenmayer, R. J. Hobbs, R. Montague‐Drake, J. Alexandra, A. Bennett, M. Burgman*, et al.*, "A checklist for ecological management of landscapes for conservation," *Ecology letters,* vol. 11, pp. 78-91, 2008.

[10] M. E. Assessment, *Ecosystems and human well-being* vol. 5: Island Press Washington, DC, 2005.

[11] M. E. Assessment, *Ecosystems and human well-being: biodiversity synthesis*: Island Press Washington DC, 2005.

[12] M. S. Reed, A. Graves, N. Dandy, H. Posthumus, K. Hubacek, J. Morris*, et al.*, "Who's in and why? A typology of stakeholder analysis methods for natural resource management," *Journal of environmental management,* vol. 90, pp. 1933-1949, 2009.

[13] A. Voinov and F. Bousquet, "Modelling with stakeholders," *Environmental Modelling & Software,* vol. 25, pp. 1268-1281, 2010.

[14] M. Burgman, D. Lindenmayer, and J. Elith, "Managing landscapes for conservation under uncertainty," *Ecology,* vol. 86, pp. 2007-2017, 2005.

[15] M. Brugnach, A. Dewulf, C. Pahl-Wostl, and T. Taillieu, "Toward a relational concept of uncertainty: about knowing too little, knowing too differently, and accepting not to know," *Ecology and Society,* vol. 13, p. 30, 2008.

[16] D. Hui, R. Biggs, R. J. Scholes, and R. B. Jackson, "Measuring uncertainty in estimates of biodiversity loss: The example of biodiversity intactness variance," *Biological Conservation,* vol. 141, pp. 1091-1094, 2008.

[17] J. Glicken, "Getting stakeholder participation 'right': a discussion of participatory processes and possible pitfalls," *Environmental Science & Policy,* vol. 3, pp. 305-310, 2000.

[18] R. W. Bosserman and R. K. Ragade, "Ecosystem analysis using fuzzy set theory," *Ecological Modelling,* vol. 16, pp. 191-208, 1982.

[19] G. Guariso and H. Werthner, *Environmental decision support systems*: John Wiley & Sons, Inc., 1989.

[20] M. Matthies, C. Giupponi, and B. Ostendorf, "Environmental decision support systems: Current issues, methods and tools," *Environmental Modelling & Software,* vol. 22, pp. 123-127, 2007.

[21] M. Poch, J. Comas, I. Rodriguez-Roda, M. Sanchez-Marre, and U. Cortés, "Designing and building real environmental decision support systems," *Environmental Modelling & Software,* vol. 19, pp. 857-873, 2004.

[22] D. W. Llewellyn, G. P. Shaffer, N. J. Craig, L. Creasman, D. Pashley, M. Swan*, et al.*, "A Decision‐Support System for Prioritizing Restoration Sites on the Mississippi River Alluvial Plain," *Conservation Biology,* vol. 10, pp. 1446-1455, 1996.

[23] D. Hamby, "A review of techniques for parameter sensitivity analysis of environmental models," *Environmental Monitoring and Assessment,* vol. 32, pp. 135-154, 1994.

[24] L. A. Zadeh, "Fuzzy sets," *Information and control,* vol. 8, pp. 338-353, 1965.

[25] R. E. Bellman and L. A. Zadeh, "Decision-making in a fuzzy environment," *Management science,* vol. 17, pp. B-141-B-164, 1970.

[26] L. A. Zadeh, "Outline of a new approach to the analysis of complex systems and decision processes," *Systems, Man and Cybernetics, IEEE Transactions on,* pp. 28-44, 1973.

[27] R. Pouwels, P. Opdam, and R. Jochem, "Reconsidering the Effectiveness of Scientific Tools for Negotiating Local Solutions to Conflicts between Recreation and Conservation with Stakeholders," *Ecology and Society,* vol. 16, p. 17, 2011.

[28] B. Fisher, "Fuzzy environmental decision-making: applications to air pollution," *Atmospheric Environment,* vol. 37, pp. 1865-1877, 2003.

[29] W. Silvert, "Fuzzy indices of environmental conditions," *Ecological Modelling,* vol. 130, pp. 111-119, 2000.

[30] V. Adriaenssens, B. D. Baets, P. L. Goethals, and N. D. Pauw, "Fuzzy rule-based models for decision support in ecosystem management," *Science of the Total Environment,* vol. 319, pp. 1-12, 2004.

[31] H. M. Regan, M. Colyvan, and M. A. Burgman, "A proposal for fuzzy International Union for the Conservation of Nature (IUCN) categories and criteria," *Biological Conservation,* vol. 92, pp. 101-108, 2000.

[32] G. Foody, "Fuzzy modelling of vegetation from remotely sensed imagery," *Ecological Modelling,* vol. 85, pp. 3-12, 1996.

[33] E. H. Mamdani and S. Assilian, "An experiment in linguistic synthesis with a fuzzy logic controller," *International journal of man-machine studies,* vol. 7, pp. 1-13, 1975.

[34] C. Wagner, "Juzzy–A Java based Toolkit for Type-2 Fuzzy Logic," in *Proceedings of the IEEE Symposium Series on Computational Intelligence, Singapore*, 2013.

[35] R. H. Froend, S. A. Halse, and A. W. Storey, "Planning for the recovery of Lake Toolibin, Western Australia," *Wetlands Ecology and Management,* vol. 5, pp. 73-85, 1997.

[36] L. A. Zadeh, "The concept of a linguistic variable and its application to approximate reasoning—I," *Information sciences,* vol. 8, pp. 199-249, 1975.

[37] C. Wagner and H. Hagras, "Interpreting fuzzy set operations and Multi Level Agreement in a Computing with Words context," in *Fuzzy Systems (FUZZ), 2011 IEEE International Conference on*, 2011, pp. 2139-2146.

[38] C. Wagner and H. Hagras, "Employing zSlices based general type-2 fuzzy sets to model multi level agreement," in *Advances in Type-2 Fuzzy Logic Systems (T2FUZZ), 2011 IEEE Symposium on*, 2011, pp. 50-57.

[39] S. Miller, C. Wagner, J. M. Garibaldi, and S. Appleby, "Constructing General Type-2 fuzzy sets from interval-valued data," in *Fuzzy Systems (FUZZ-IEEE), 2012 IEEE International Conference on*, 2012, pp. 1-8.

[40] J. M. Mendel, "Uncertain rule-based fuzzy logic system: introduction and new directions," 2001.