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Article

Meeting Human and Biodiversity Needs for 30 × 30 and beyond with an Iterative Land Allocation Framework and Tool

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Abstract: Spatial conservation prioritization does not necessarily lead to effective conservation plans, and good plans do not necessarily lead to action. These "science-action" gaps are pernicious and need to be narrowed, especially if the international goal of conserving 30% of the planet by 2030 is to be realized. We present the Earthwise Framework, a flexible and customizable spatial decision support system (SDSS) architecture and social process to address the challenges of these science-action gaps. Utilizing case study experience from regions within California, South Africa, and British Columbia, we outline the framework and provide the Little Karoo, South Africa SDSS data, code and results to illustrate five design strategies of the framework. The first is to employ an "open science" strategy for collaborative conservation planning and action. Another is that marginal value functions allow for the continuous accounting of element (e.g., habitat) representation in prioritization algorithms, allowing for an SDSS that is more automated and saves valuable time for stakeholders and scientists. Thirdly, we program connectivity modeling integrated within the SDSS, with an algorithm that not only automatically calculates all the least cost corridors of a region, but prioritizes among them and removes the ones that do not make ecological sense. Fourth, we highlight innovations in multi-criteria decision analysis that allow for both cost-efficient plan development, like representative solution sets, but also land-use planning requirements, like site specific valuation, in what appears to be a more transparent, understandable, and usable manner than traditional approaches. Finally, strategic attention to communicating uncertainty is also advocated. The Earthwise Framework is an open science endeavor that can be implemented via a variety of software tools and languages, has several frontiers for further research and development, and shows promise in finding a better way to meet the needs of both humans and biodiversity.

Keywords: spatial decision support system; collaborative conservation planning; habitat connectivity; habitat representation; 30 × 30 commitment; EEMS; OECM; LandAdvisor; Earthwise Framework

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1. Introduction

The Earth is undergoing a biodiversity crisis, losing species at over 1000 times the background rate [1], and losing approximately 70% of its wild animal population since 1970 [2]. The call to conserve 30 percent of the Earth's land and oceans by the year 2030 (i.e., 30 × 30) is now widely adopted, as evidenced by the historic "Kumming-Montreal Global Biodiversity Framework" agreed to by nearly every country in the world [3]. It remains to be seen how successful we will be at meeting that target, and if the 30% protected will be one of the scenarios designed primarily to conserve biodiversity or to maximize natural resource extraction [4]. To achieve the best possible outcome for biodiversity, it is necessary for scientists and practitioners in the field of systematic conservation planning (SCP) to gather their findings and lessons learned from years past and share them with people newly mandated to achieve 30 × 30 specifically, and conservation outcomes more generally. This paper fulfills this call, coalescing 15 years of applied research.

SCP is a science-based process for prioritizing where land should be conserved and for developing strategies and plans for achieving this conservation [5,6]. Conservation assessment and design (i.e., spatial conservation prioritization) is the underpinning of SCP; it is the scientific evaluation of valued elements of nature to help people decide where on the landscape to allocate scarce conservation resources [6]. These assessments are then used to devise an implementation strategy: who is responsible for doing what, where [7,8]). In the ideal scenario, conservation actions are then implemented, monitored, and re-evaluated in an adaptive management process. However, there is a common frustration that SCP does not yield enough on-the-ground action; there is often a gap between assessment and planning, and then between strategy planning and implementation (also summarized as the science-action gap) [9–12]. The objective of this paper is to help close these gaps, putting forth five strategies for implementing SCP and 30 × 30 effectively, including an analytic and social framework for implementing these strategies, then illustrating the framework and strategies through a case study in the Little Karoo, South Africa. To facilitate further research and discussion with a shorthand name, we concluded our research by naming the analytic and strategic framework the Earthwise Framework. (Previous communications, software user-guides, etc. used "LandAdvisor" but we have changed the name for several reasons, including being more inviting to marine and land–sea interface endeavors).

South Africa had a relatively peaceful revolution and then a new constitution in 1994, complemented with enabling legislation like the National Biodiversity Act, thereby propelling it to be a world leader in the theme of conservation planning for implementation (see [13–15] for more context). Hence, we chose it as the location to further develop and illustrate the Earthwise Framework.

An overarching theme of this manuscript is that careful attention to spatial decision support system (SDSS) design is key to helping close the science-action gap. An SDSS combines data, science, and human values in a transparent manner to provide integrated computer maps, tables, figures, and text to help people make decisions about what to do where. An SDSS does not make decisions, but supports deliberation and decision making at any stage of the conservation cycle.

2. The Four Implementation Challenges

Four major challenges to implementing systematic conservation plans include increasing engagement, integration with land-use planning, building "living" and adaptive modeling systems, and getting beyond a binary characterization of conservation. In the final chapter of "Spatial Conservation Prioritization" [16], 38 authors ranked the 37 methodological topics of the field, and highlighted seven top topics as being important, relatively overlooked in the past, and likely to be extensively researched in the near future. Three of these align well with the four challenges identified above; they called for (1) preparation of publicly available resources (software, GIS layers, data collection) (2) integrated planning methods, and (3) methods for computationally dealing with multiple conservation actions.

2.1. Engagement and Understanding

Translation of conservation planning to implementation requires careful examination and engagement of the socio-political context within which such action occurs. Engaging citizens, other stakeholders and decision-makers right at the beginning of planning processes is critical [6,17–19]. It is important to develop an operational model (i.e., a framework) that accounts for socio-political context and identifies the different phases, products, and goals of a process [6]. A key in many contexts is the goal of establishing social learning institutions that practice adaptive co-management [6,15,20]. However, there has been little discussion about the role that a SDSS can play in such operational models in general, and the goals of learning and co-management specifically. A well-designed SDSS can provide backbone support to every phase and iteration of the operational model (e.g., Figure 1).

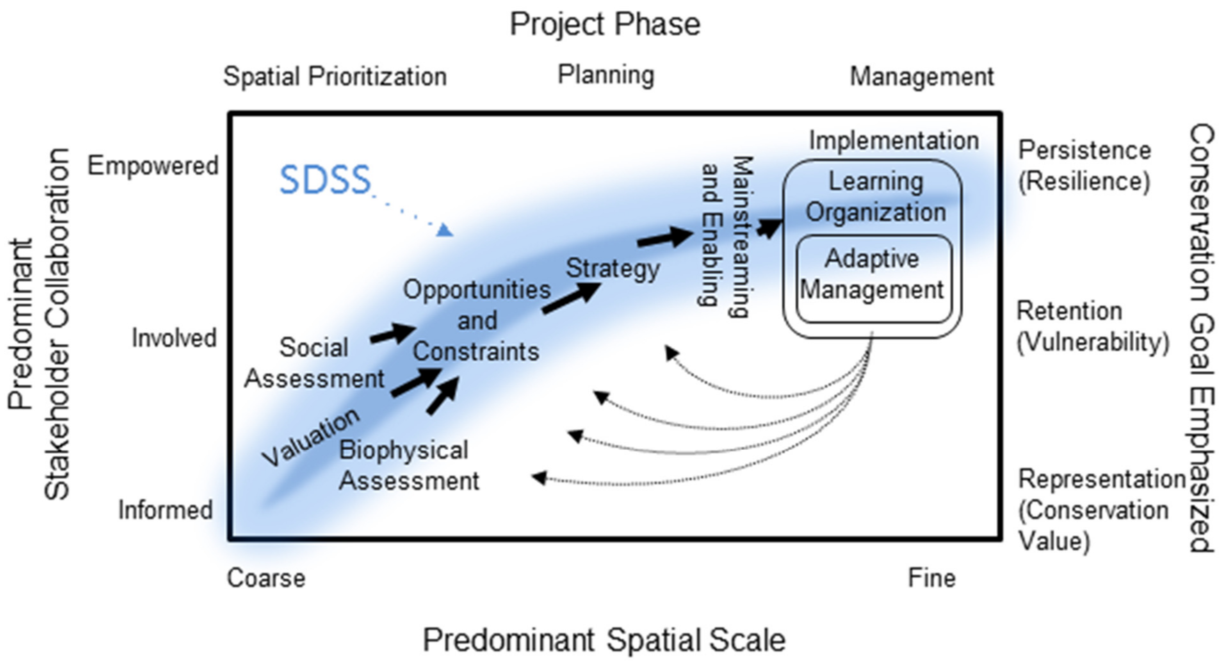

Figure 1. An operational model with an emphasis on engagement, being supported by an SDSS. A well designed SDSS can expand over time to support all phases of the conservation planning operational model. (Adapted from [6,15,21]).

The planners, stakeholders and decision-makers engaged in the land-use change process can collectively be called the targeted end-users of an SDSS. An underlying assumption is that the more people that understand, buy in to, and use an information system, the higher the likelihood of effective, streamlined conservation actions. If the SDSS is too simple, then it may be ineffective at addressing the extremely complex problems it is meant to help solve. However, if it is overly complex and confusingly designed, potential end-users may not understand it, and will be less likely to trust the results or use the system. The challenge is for the SDSS to adequately represent intricate and often complex human-nature interactions, without performing as a "black box". A strategy is to remove barriers to entry and scaffold the complexity such that the participants can quickly understand the logic of the entire model and can learn incrementally more detail as required by their needs. A related strategy is to motivate this engagement by providing opportunities for participation, such as to contribute objective and subjective data (e.g., citizen science observations and polling about parameter values such as relative weights). The challenge becomes implementing these transparency and engagement approaches cost-effectively while also maintaining logical consistency and scientific rigor.

2.2. Integrate with Land-Use Planning

Another goal of SCP is to better interoperate with land-use planning [6,8,22–24]. Land-use planning attempts to balance a variety of competing needs in what can be thought of as "planning for development". It is inherently about tradeoffs, and has profound implications for biodiversity conservation. SCP has traditionally operated in isolation from land-use planning and policymaking even though conservation acquisitions often just shift development around [24]. In rare cases SCP results are used as a reference for land-use planners to consider (e.g., [23]), which is a good start. This approach can be extended such that the tools and frameworks of SCP are expanded to evaluate a more comprehensive set of needs and tradeoffs and merge better with land-use planning. Some agencies and organizations are framing this as targeting the triple bottom-line of equitable ecological, social, and economic sustainability (e.g., [25]). We speculate that if, instead of looking at the single principle objective (i.e., where to conserve), SCP could expand to look at multiple objectives (e.g., where to conserve, where to develop, where to farm, where to log, etc.) in a manner that meets ecological principles, then great progress would be made in achieving implementation of conservation objectives. An incremental step towards this end is to effectively include economic and social objectives while planning for multiple conservation objectives [16,26].

SCP has often focused on providing solution sets (of planning units) as the primary means of providing decision support. A solution set or "conservation area network" (CAN), is a large number of units that, in aggregate, meets a conservation planning objective such as maximizing the persistence of biodiversity features with a given budget, or minimizing costs given a targeted level of biodiversity benefit [16,27]. However, a majority of the implementation decisions about changing land ownership or management occur on a local or site-by-site basis, not on entire solution sets [6,12,22]. The process of assessing and planning for the triple bottom line should provide solution sets, while also clearly communicating the relative importance and characteristics of every planning unit (Figure 2). Traditional solution set algorithms do often have by-products that can indicate the value of a particular site (e.g., [28]), but it is hard to know why a site received high or low value. Decision-makers should be able to quickly and easily click on a planning unit on a computer map and see what its relative values are for all the input criteria, and how those values compare to all planning units in the study area and/or its sub-area. To be clear, SCP is context specific, and there are still cases where the solution set algorithm is a higher priority than the site valuation/communication algorithm.

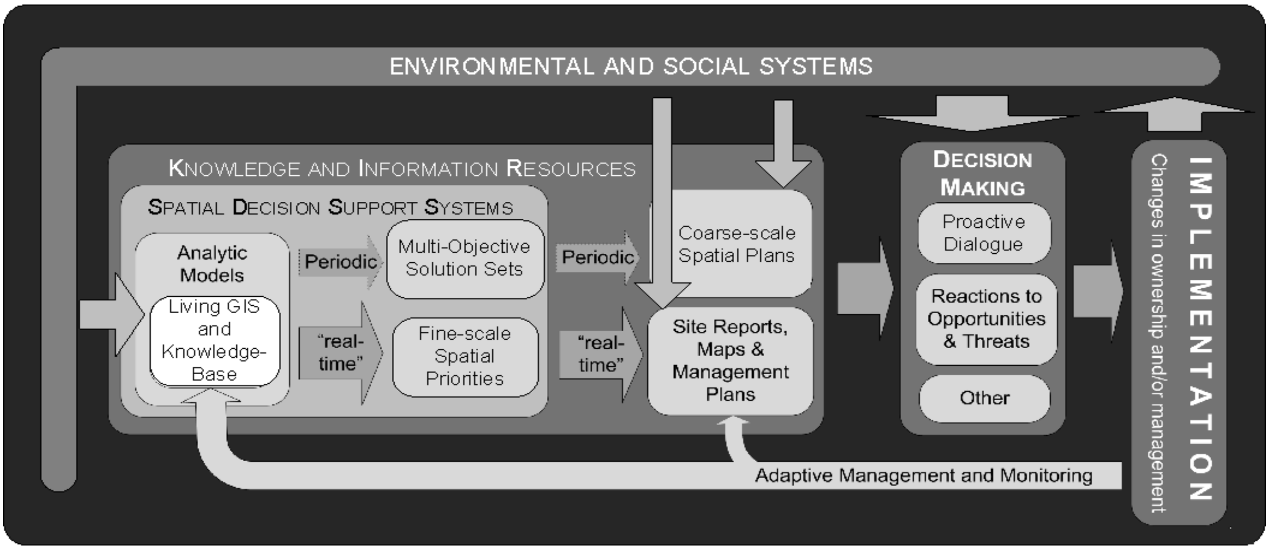

Figure 2. Multi-scale and contextual framing of a "living" SDSS. Ideally a "living" SDSS is able to incorporate new data from adaptive management and monitoring, and provide useful and user-friendly products at multiple scales.

2.3. Adaptive Planning and the Need for "Living" SDSS

We live in a dynamic, political, and uncertain world. As a result, conservation plans are almost never implemented as originally planned [29]. They quickly become out-of-date and sub-optimal [30]. One response has been to redouble efforts to model the future and to plan accordingly [31]. This can manifest as trying to sequence what parts of a conservation area network solution set should be implemented first (e.g., [32]), or as predicting climate change outcomes and planning accordingly [33]. Our observations are that this strategy is important, but it is very data intensive, complex, and may face diminishing returns. An alternate approach is to view conservation plans not as static processes but rather as starting points for ongoing adaptation [12]. This is a key element to many planning frameworks, such as the Steinitz Framework [34,35], the open standards for conservation [36], and the one adapted in Figure 1.

A pragmatic challenge for such adaptive planning lies in the logistics. Data, hardware, and software become outdated quickly, so that when it comes time to update a plan, sometimes years later, it is usually easier to start the process over if the workflow has not been maintained. As a result, a major funding and institutional push needs to occur, and hence, the adaptations are likely delayed for years. We need to transition from one-off conservation planning assessments to building planning tools, workflows, and institutional capacity to easily facilitate adaptive and iterative planning processes. The creation and use of "living" SDSS would give us the flexibility and adaptability previously lacking.

The term "living" has several components in this context. First, the data and analyses should be as up-to-date as possible. As new data and information about the world become available, they should be integrated in to the SDSS (as automatically as possible), and end-users should have the option of viewing updated SDSS outputs. For instance, if a land trust tries to pursue a solution set (i.e., CAN) for a year and acquires several properties, some of which were not in the original solution set, and also finds that several properties in the solution set have landowners unwilling to sell at any reasonable price, and are also unwilling to enter into an easement, then the relative value of all the planning units, and the best solution set, have both changed, and in some cases changed dramatically. The entire analysis should be updated given these new data (Figure 3). Secondly, the system, while focused on the regional scale, should span from the local scale (e.g., parcel or cadaster management) to the national scale. For the fine scale the system should support management decision-making and incorporate new monitoring data, and for the coarse scale the system should provide regional guidance and incorporate national level results/priorities. Similarly, two scales of analysis can be performed (e.g., county and state extents) using the same framework, with the results of the coarse scale analysis feeding into multiple fine-scale analyses, whose results feed back into the next coarse scale analysis, and so on. Thirdly, a living SDSS should grow, expanding over time with additional criteria, new parameters, new scientific understanding/models, and changing social values.

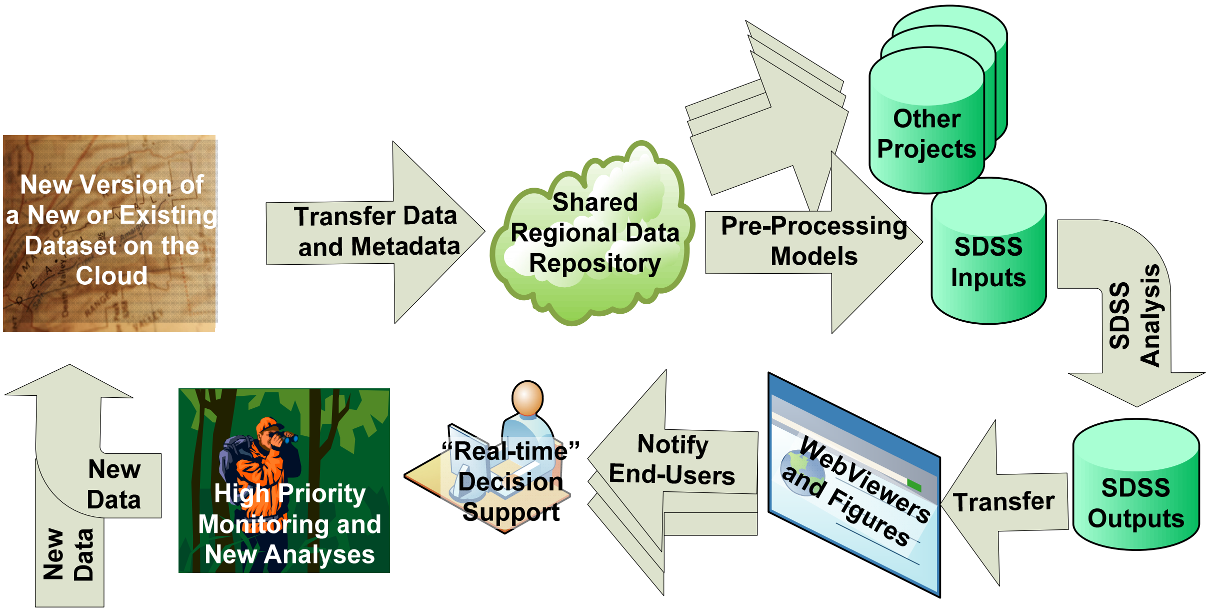

Figure 3. Simplified workflow of a "living" SDSS (spatial decision support system), which is able to provide updated products as conditions change. A challenge in a "living" SDSS is to automate, as much as practical, all the steps within each arrow, and eventually, the linking of all the arrows.

Some of the key sub-challenges to target in pursuing this broader challenge are automating workflows as much as possible, minimizing the number of software components that need to be maintained, leveraging collaborative relationships, and retaining institutional knowledge to mitigate inevitable staffing turnovers.

2.4. Beyond Binary Characterization

Gap analysis is a systematic approach to identifying biodiversity elements (e.g., habitat types) that are not very well protected in reserves and other land management units that help conserve biodiversity [37]. These "gaps" can then be conserved. This strategy assumes that if representative samples of the different niches (habitats on which a species depends) in a region can be conserved, then most of the species and ecosystem functions will be conserved as well. It is then combined with a fine filter approach to make sure no special elements (e.g., rare, geographically restricted species) fall through the cracks.

To operationalize the principle of representation, scientists in the 1990′s made optimization algorithms that were helpful, but not nuanced. The algorithms required a single threshold amount (or target) for each element that was the reasonable amount required for conservation. However, determining that "reasonable amount" is difficult: at its core it is a political and cultural value judgment about how much biodiversity loss and risk is acceptable. Secondly, the algorithms would assume lands were either conserved or not conserved. However, in reality, conservation is a gradient, which needs to be built into conservation planning algorithms [27]. Thirdly, in many cases they would not distinguish between pristine locations and more degraded locations. All hectares were counted equally. These assumptions introduce large degrees of uncertainty that our experience has shown decreases the trust that ecologists and land-use stakeholders place in the ensuing "optimal" or "near-optimal" outputs. Decreases in trust yield decreases in use. Hence, the fourth challenge that this research helps address is how to get beyond the need and use of binary measurements for (1) target achievement, (2) conserved area, and (3) naturalness.

3. Methods and Materials for the Five Strategies

3.1. The Earthwise Framework and Example SDSS

To address these four challenges: we maintain that SDSS for conservation planning should be constructed to be integrated, understandable, automated, multi-scale, and expandable. Towards these ends we suggest the strategies in the following sections, and illustrate them with an Example SDSS. Table 1 summarizes how the strategies address the challenges.

The Example SDSS is an instance of the customizable Earthwise Framework. A framework identifies broad guidelines and structural suggestions, but the details, such as software type and tools, can be determined by every team. The framework builds upon the one developed by Davis et al. [38] and combines novel and conventional modeling methods for maximizing the ecological component of conservation, while considering the economic and social components as well. It is modular and expandable, allowing for the eventual maximization of all three components in aggregate. The SDSS of the Little Karoo, South Africa application is the one highlighted in this paper, does most of its calculations in the raster environment, and is here termed Earthwise-LK. It is open access (cited in the Results) to allow for further use, development, evaluation and/or incorporation into software or other tools. As such, the Framework has been applied in at least four other regions, each with a different customization [39].

The emphasis of this paper is not on all the details of the SDSS but more on describing strategies that are transferable to other systems, and demonstrating that they can be integrated into a single software system. Additional details regarding Earthwise-LK are provided in Supplementary Materials S1: User Guide.

Table 1. A matrix summarizing how the strategies address the challenges.

Challenges ↓	Engagement	Land-Use Planning	Living SDSS and Adaptive Planning	Beyond Binary Characterization
Strategies↓				
Open Science	Allows public participation in science, and co-learning	More data, monitoring, and transparency	Facilitates distributed collaboration and software development	Helps gather data for Quality Weighted Area
Marginal Value Functions	No need to negotiate target thresholds	Provides representation value for every parcel	Tracks changes in representation in real-time	Measures fractional representation achievement
Automated Connectivity		Adjusts linkages as conditions change	Integrates connectivity into valuation and solution sets	Indicates priority among linkages
MCDA Innovations	Intuitive and more accessible	Transparent valuation of planning units	Integrated platform; spans from site to national scales	Yields a range of values
Communicate Uncertainty	Shows hubris, builds trust	Helps plan by indicating confidence	Identifies research and data priorities for next iteration	Shows variance

3.2. Strategy One: Open Science

In general, successful leveraging of the internet entails being open, sharing your work, collaborating, and being multi-scale [40]. An underlying hypothesis of this strategy is that applying these principles to conservation planning will allow a more cost effective route to broader public engagement, as well as to furthering the data and science necessary for living and integrated land-use planning. A driving assumption is that as more people get meaningful opportunities to help in "keeping nature's benefits" in their home region, then an increase in understanding about nature will ensue, leading to more empathy, and commitment to stewardship. One way to help close the science-action gap is to recognize that SCP is transdisciplinary and needs to be influenced by, and influence, not only empirical, pragmatic, and normative knowledge, but also the important and largely overlooked purposive knowledge (e.g., societal values, and the dominant social paradigm) [11]. An underlying hypothesis is that collaborative development and use of a well-designed SDSS yields ecologically grounded normative outcomes consistent with society's purposive knowledge, while beneficially affecting society's purposive knowledge as well.

3.2.1. Collaborative Conservation Planning and Action

Data-driven intelligence (DDI) is a key concept of the open science strategy. In contrast to artificial intelligence, DDI is a very different approach to finding meaning that complements rather than mimics human intelligence [41]. It utilizes computer processing and architecture to make sense of vast datasets in a way that the human mind cannot possibly compute. It does this using code that can be incredibly complex. While Artificial Intelligence (AI) can create similar code, and both can be released open source, there is a distinction. Unlike much AI generated code, the justifications for the DDI code and parameter values used are traceable and if best practices are used, are transparent and documented. Some problems are more suited to solving using DDI, others by human intelligence, and still others, such as land-use planning, that can benefit by drawing from both.

The vast datasets utilized in DDI can be generated via traditional means as well as by smart sensors (i.e., Internet of Things), experts, and by the public via public participation in scientific research (PPSR).

The field of PPSR (also known as citizen science, community science, and c* science) provides helpful practices, networks, and resources for making DDI as useful and cost effective as possible [42–44]. There has been an increasing disconnect between people and nature with a rapidly urbanizing population that cares less about the environment (e.g., [45]). PPSR has the potential to not only provide huge quantities of basic data never before possible, but also to reconnect people to nature, building understanding, empathy, a sense-of-place, and behavior change [46]. Because of its intersection with mobile technology and even gamification, PPSR can appeal to people, youth especially, that love their phones and games and are not already engaged with keeping nature's benefits; PPSR becomes "cool" via the app or game.

However, this vision for collaborative conservation planning and action via the Earthwise Framework is not just about knowledge development and sharing, but also about decision-making. The same principles for successful leveraging of the internet apply. In the case of decision-making about public land and/or policy this draws upon the new field of open government [47–49] and its foundational principles of collaboration, transparency, and participation. The roles and information flows for these processes can be summarized as in Figure 4. Over time, the Earthwise Framework can facilitate the interplay between and among more of the hierarchical levels and parallel domains of our society: jurisdiction, management, institution, time, area, and knowledge [50].

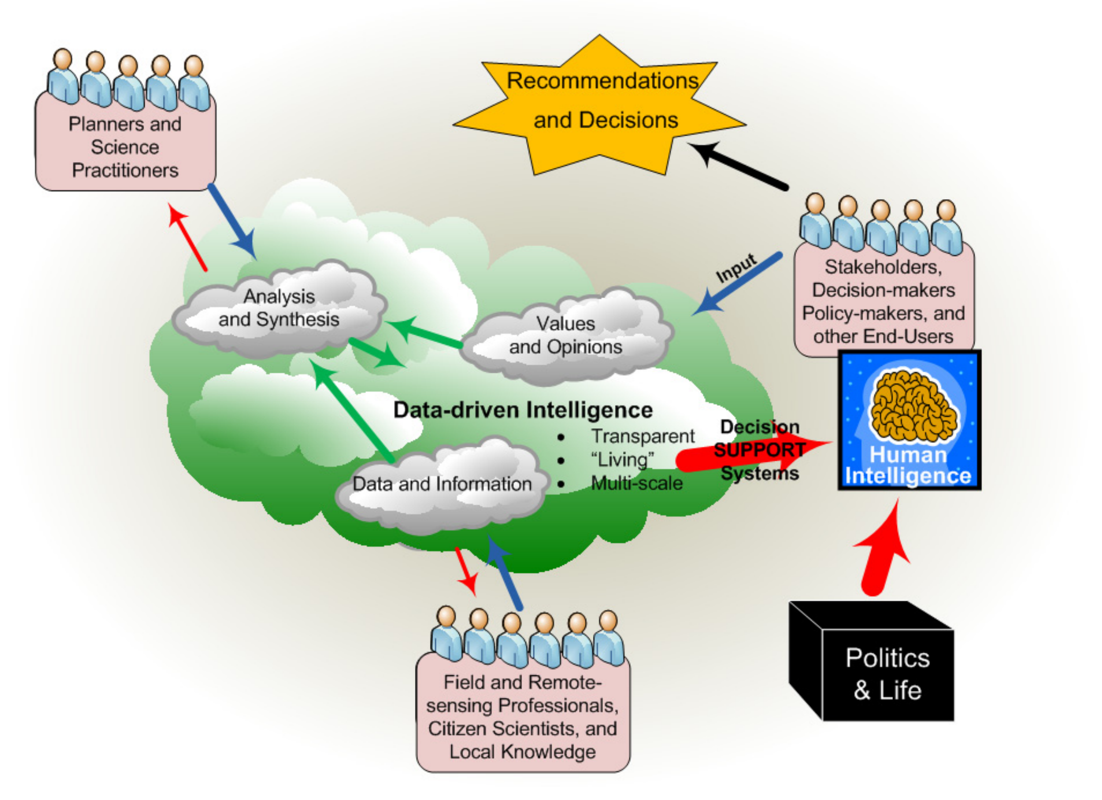

Figure 4. Knowledge flow and contributions in the Earthwise Framework. Individual people or organizations can play a role in multiple locations. Despite heavy reliance on the internet and asynchronous participation, in-person interaction is critical to strengthening relationships and should be built into the learning organizations.

This general vision translates into a strategy for SDSS development by providing a context and guidance for research and day-to-day decisions. One can ask: how can I help hone this vision and how does my research/design decision at hand move us towards this vision? The rest of this paper provides specific SDSS design features and frontiers that are experimental increments towards enabling this and similar visions for open science, open government, PPSR, and land stewardship.

3.2.2. Collaboration among Scientists

One of the ways to realize the vision of collaborative conservation planning and action is to remove the traditional barriers to scientific collaboration among teams to increase the velocity of scientific innovation and knowledge-building [41,51]. Development of the Linux computer operating system is a good example of what can be done when these barriers are avoided. The Linux kernel (core code) was released open-source in 1991, and thousands of self-organized people worldwide have since contributed to its development, which is ongoing [40]. It is the leading operating system on servers, and as of November 2013, more than 96% of the world's 500 fastest supercomputers run on some variant of Linux (unpublished data). Further, it has been ported to more computer hardware platforms than any other operating system, many without being recognized. For instance, Android is built on top of the Linux kernel. The Human Genome Project is another good example. It illustrates a watershed moment in which number of pharmaceutical companies abandoned proprietary human genome sequencing to instead submit them to open repositories, allowing discovery to occur faster by several orders of magnitude [40,41].

3.3. Strategy Two: Marginal Value Functions

Marginal value functions (MVFs), sometimes termed functions of diminishing returns [29,38,52,53], are a recent innovation in conservation science that can be further refined to address all four of the challenges outlined earlier. MVFs implement the principle of representation. Their logic is that as more area of a particular ecologically significant element is conserved; the relative benefit to biodiversity of conserving the next location of the element diminishes. For the purposes of discussion, we will use habitats as the class of ecologically significant elements, but the same principle applies to other classes such as land facets [54]. Given any land-cover and land-use scenario, as well as the parameter values set by a scientist or team of scientists, MVFs automatically calculate the relative value of conserving any particular habitat type. Hence, the relative representation value of any unit area on the landscape is calculated and when the landscape changes, such as with new development or protected areas, the estimated conservation values of places are automatically recalculated.

MVFs work as follows. The percentage of the habitat conserved at any given moment corresponds to a point on the MVF curve, thereby giving a quantitative measure of benefit (Figure 5). The power of this strategy comes from the ability to automatically define the shape of each habitat's MVF curve to reflect important conservation planning practices.

Davis et al. [38] introduced the nuance that the end users have the ability to define a threshold of critical importance, up to which every unit area conserved is equally important. They also have the ability to suggest that after a certain high level of conservation any additional conservation is not important (the "None" MVF of Figure 6). Further, many regional efforts have already established targets (e.g., the goal of conserving 30% of a particular habitat). Targets provide a good benchmark for measuring progress, are simple to convey, and have several other socio-cultural merits [55]. In some cases, they can be linked to high likelihoods of transitioning to an alternate ecological state. Hence, we include the option to use targets in the MVF [52]. Further, we provide a parameter for how much influence target attainment has on conservation of the element. The parameter could be set so that the MVF has an inflection point at the target, drops vertically a certain percentage towards zero, or drops all of the way to zero (e.g., low, medium, and high influence) (Figure 6).

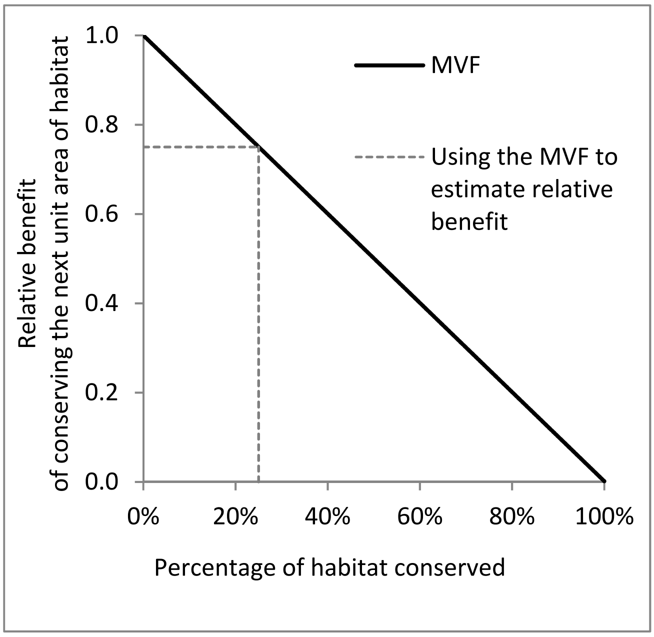

Figure 5. A simple marginal value function for determining relative benefit in a representation analysis. If an example habitat has 25% of its extent protected, and has been assigned this simple marginal value function (MVF), then the relative benefit to biodiversity of conserving the next unit area of this habitat is $\frac{3}{4}$ of what it was to conserve its first unit area.

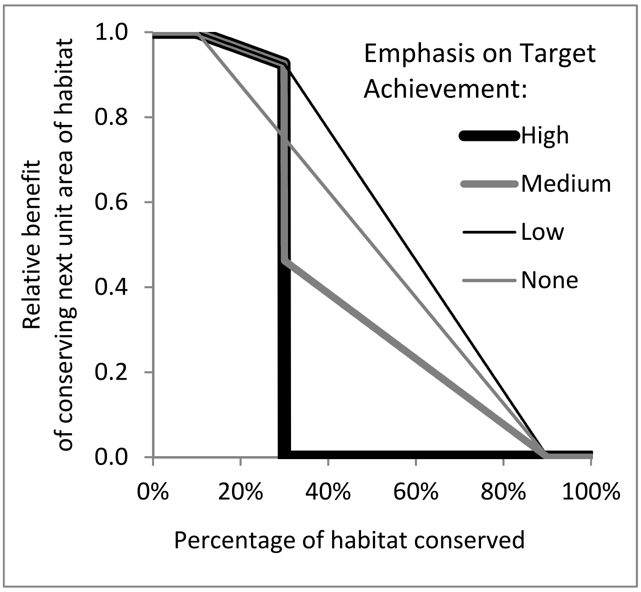

Figure 6. Four marginal value functions that exhibit differing emphases on target achievement. Traditional conservation planning identifies a representation target for how much of each habitat should be conserved in reserves. Here, are four marginal value functions (MVFs), three with a target of 30% and different "target emphasis" parameter values, and one with no target at all.

Advanced Criteria

We posit that in many cases an automated alternative to the often costly and contentious target selection and re-evaluation cycle would benefit the planning process and stakeholder relations. To explore this path, we automatically defined the shape of the MVFs based on factors that are often used in determining targets, and that influence relative conservation priority of different elements. We include past conversion of the habitat, condition weighted area, and designation weighted area, all described below.

First, we account for habitat conversion (i.e., vulnerability) in the relative shapes of the FDR curves. A vulnerable element in this case is one that has had much of its historic range degraded or lost. For an example, we'll consider the study region of the Earth, and biomes as the elements. An analysis found that 45.8% of the world's historical temperate grass-shrublands have been converted to human uses, compared to only 2.4% of the boreal forests [56]. So if each biome had the same percentage of historical habitat now conserved, according to this metric it would be of much higher value to conserve the next unit area of grassland than boreal forest [56]. To implement this logic, the automated MVF assigns a higher Y-intercept to the element that is more degraded. The maximum value is one, and the user defines the minimum value. The actual values are then distributed linearly between the minimum and maximum (Figure 7).

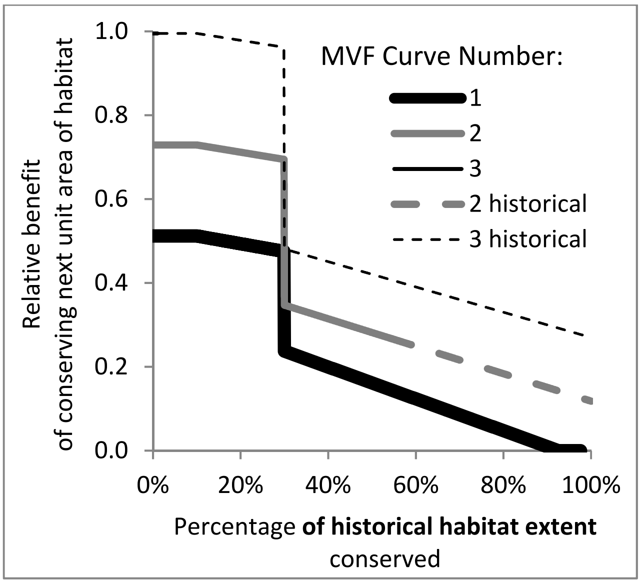

Figure 7. Adjusting the relative marginal value function based on habitat specific historical degradation. As a habitat is degraded, its marginal value function (MVF) rises in value relative to the other habitats. Using the parameters of the medium target emphasis MVF of Figure 6, and global habitats example [56], line 1 represents an element that is 97.6% intact (e.g., boreal forest biome globally), line 2 represents an element that is 54.2% intact (e.g., grassland/shrubland biome), and line 3 represents a hypothetical element that has lost 99% of its historical extent. In this case, the parameter value for differentiating these habitats up and down the Y-axis is set to 0.5. The dashed lines represent habitat already lost.

"Condition-weighted area" [38] is another advanced feature implemented in the Little Karoo Earthwise instance. This is the notion that conserving a pristine unit area of habitat is more important to representation goals than conserving a highly degraded unit area of that habitat. To implement this, every unit area (e.g., grid cell) on the landscape is assigned a naturalness value based on surrogates such as road density, building density, remote sensing data if available, etc., and naturalness value is multiplied by the unit area to get condition weighted area. We further this by introducing "designation-weighted area" which recognizes that different forms of conservation have varying levels of satisfying representation goals. An example taxonomy is the International Union of the Conservation of Nature (IUCN) protected areas classification. This "shades of grey" approach allows IUCN Category VI (protected area with sustainable use of natural resources) to be incorporated into representation algorithms (rather than being ignored as is tradition) using a "management allocation value" that is lower than that of IUCN 1a (strict nature reserve).

The science advisors and/or end users of the SDSS determine the relative management allocation value of each conservation classification. This allows for privately owned conservation areas, which can be extremely significant in some regions (e.g., [57]), to be accounted for in the representation analysis. The "quality-weighted area" (QWA) of a unit area is the condition weighted area multiplied by the designation-weighted area, and determines the location on the X-axis to be used on the MVF in calculating relative benefit (Figure 8).

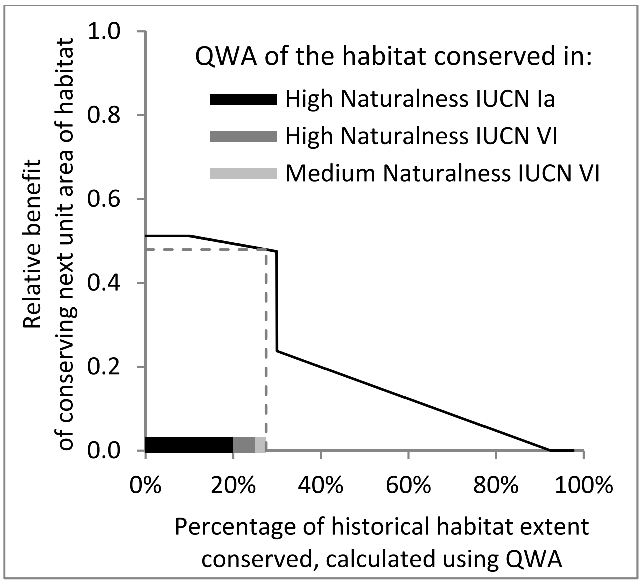

Figure 8. Using quality weighted area (QWA) to determine how much of a habitat is "conserved". This is the example MVF for the boreal forest biome of Figure 7. In this hypothetical snapshot in time, 20% of its historical extent is conserved in each of the three condition/designation combinations. If the parameter values for medium naturalness value is 0.5, high naturalness is 1.0 (the max. value), IUCN VI land has a designation-weighted value of 0.25, and IUCN 1a land has a designation-weighted value of 1.0 (the max. value) then the QWA conserved of the above scenario is 27.5% of historical, translating to a relative benefit of 0.48 for conserving the next unit area of boreal forest. As more highly natural or medium-natural land gets conserved, in working landscapes or in reserves, this value decreases accordingly.

Again, all of these curves and values are automatically calculated given a set of parameter values and current data or data scenario. Details about the parameters, and the formulae used, are provided in Supplementary Materials S1: User Guide. To facilitate the exploration of these parameters, we created an Excel graphing application, Supplementary Materials S2: Calibrating the Marginal Value Functions, that allows the end-user to explore the above figures and to plug in different input and parameter values to see how the corresponding MVFs change.

3.4. Strategy Three: Automated and Integrated Connectivity Modeling

The principle of landscape connectivity is that large core reserves should be connected by linkages of decent habitat to facilitate gene flow, population movements, and ecological processes [58]. This principle is gaining even more importance in the face of climate change, as such linkages will allow the natural movement of species to new locations in pursuit of their preferred climes [59,60]. There are many GIS models, summarized below, that can be used to estimate the location and priority of planning units to be managed as portions of such linkages. Our primary suggestion is that these models should be improved to be as automated as possible, and integrated into a living decision support system.

Some approaches use a "least-cost corridor" methodology to estimate the location of a linkage between two core areas of habitat (e.g., [61]). Some use circuit theory to estimate such a linkage (e.g., [62]). The former appears to better define the varying width and braids of a linkage, while the latter effectively quantifies the pinchpoints in a linkage. Others combine both of these methods in sequence to get the best of both [63]. Still others use the underlying resistance surface input, but do not require core areas as an input in mapping out connectivity areas [64,65]. The degree to which these map landscape linkages is not clear though. However, all of these require a GIS analyst to be involved to some extent before the output can be used as an input to the next analysis of an SDSS. We have created a connectivity algorithm for review and evaluation that aims to gain the robustness of core-pair analyses while also being automated for any landscape. It requires little GIS analyst time, but it does require significant computer processing time. The assumption is that with Moore's Law about exponential improvement in computing power [66], this "brute force" approach will require minutes instead of hours in the near future. (In other work [60], we programmed an alternate approach to modeling connectivity priority, and the two techniques have yet to be formally contrasted and compared.)

3.4.1. Method Overview

Least cost corridor techniques require identification of the core areas that need to be connected, and a cost (i.e., friction) surface [61]. Our model provides the GIS Analyst with a variety of parameters to use in performing this pre-processing, including the option of increasing the relative value of stream corridors (See Supplementary Materials S1: User Guide). The connectivity algorithm then creates and combines least-cost corridor, permeability, and least-cost-path length outputs for every pair of core areas on the landscape (that are less than a user-defined distance apart). All the outputs are overlaid, selecting the maximum value for any particular location and removing the corridors that do not make theoretical sense (according to the parameter value set by the GIS Analyst). The output is then automatically fed into the site selection model, described in the next Strategy.

3.4.2. Method Detail

A least-cost corridor analysis is performed using the cost layer and the locations of each pair of core areas on the landscape. Defining the maximum distance allowed between core areas as something smaller than the width of the study area exponentially decreases processing time by avoiding the analysis of core pairs that are on opposite sides of the study area. The raw product of each pair analysis yields a connectivity value for every cell on the landscape, and a user-defined parameter defines what percentage of the best cells to keep. The resulting Least-Cost Corridor output is divided by the total cost of the corresponding least-cost path, inverted and normalized (such that the cells along the least cost path get a value of 1, and the cells at the outer edge of the corridor get a value just above 0). This product is termed the "Connectivity Envelope", and has varying widths, often with braids.

One of the problems with the traditional Connectivity Envelope is that it does not distinguish the relative value of linkages between different pairs of core areas. Some mapped corridors may contain lower quality habitat, while others traverse higher quality habitat. The Permeability Index addresses this problem, and helps make the process automatic. It is calculated by first dividing Least-Cost Corridor by the length of the Least-Cost Path to derive impermeability values for each core pair. Linkages that traverse a high percentage of high quality habitats will have a high relative permeability. The permeability output is obtained for every pair of cores, which are then normalized and inverted such that the least-cost path of the most permeable corridor gets a value of 1, and the lowest value of the least permeable corridor will get a value of 0 (Supplementary Materials S1: User Guide).

A final assumption is that if two different linkages have the same maximum permeability value, but one is much shorter than the other, then the cells in the shorter linkage should arguably get a higher relative connectivity value, as there is less chance that the wildlife individuals traversing the linkage will be harmed. Each Corridor Envelope is then assigned a value between 0–1 with the shortest one on the landscape getting a value of

1 (Supplementary Materials S1: User Guide). This yields the Least Cost Path Length for every pair of cores.

The weighted sum among the Connectivity Envelope, the Permeability Index, and the Least Cost Path Length is performed for each pair of cores. The outputs of all these weighted sums are overlaid, and the maximum value of a cell among all the layers is selected for the output layer. The final connectivity map is then normalized such that the highest valued cell that is part of the highest valued corridor on the map is 1, and the lowest valued cell that is a part of the lowest valued corridor is 0.

3.5. Strategy Four: Innovations in Multi-Criteria Decision Analysis

According to the Spatial Decision Support Consortium's knowledge portal [67] based heavily on [68], the term multi-criteria decision analysis (MCDA) includes both multi-attribute overlays [69] and multi-objective analyses [70]. For multi-attribute overlays, several attributes that are spatially distributed and contribute to a single goal (such as soil organic content and groundwater level contributing to an agricultural suitability analysis) are mapped as quantitative values across the landscape, and then all the values that overlay on a planning unit are combined, such as with a weighted sum. Attributes that are deemed highly important can be given a higher weight in the sum. Boolean logic, fuzzy logic, and other mathematical operators can be used instead of weighted sums.

Multi-objective analyses, on the other hand, cannot be operationalized through a single multi-attribute overlay. An example multi-objective problem is: identifying a portfolio of sites to conserve that is 30% of a defined area, and as a complementary whole maximizes biodiversity conservation and minimizes cost to society. Within this, maximizing biodiversity conservation could include making sure that all the habitat types in the area have at least a minimum level of protection in the portfolio (the more the better), and the portfolio is adequately connected to allow for biodiversity gene flow. Multi-objective problems can be supported using multi-level or stepwise multi-attribute overlay, but are generally approached using mathematical optimization or near-optimal heuristic methods. Because SCP problems have a large number of possible "solutions" (possible outcomes by planning unit), they have traditionally relied on heuristic methods. The Classic SCP approach e.g., [71] can be characterized as follows:

- Build a large number of possible solution sets (possible far-off future states, often based on hard percentage representation targets), and assess the representation efficiency/complementarity of each.
- Rate the relative conservation importance of planning units by assessing how often they occur in good solution sets (their irreplaceability).
- Include additional objectives in the efficiency assessment, either as benefits to be simultaneously maximized, or as acquisition or opportunity costs to be minimized.
- Select the best heuristic solution set.

Additionally, such a process usually yields an outcome in which there is good contiguity (clumpedness) of conservation areas, but not necessarily connectivity among conservation areas with narrow linkages. A connectivity analysis is often then performed ad hoc, or after an initial optimal solution set is attained, and then manually added to the solution set before a final solution set analysis.

We are advocating an approach that combines multi-attribute overlay with spatial context values in an iterative allocation cycle (also known as a "greedy" heuristic), as follows:

- Use multi-attribute overlay based on the current situation, including continuous MVF-based representation value, to rate the relative composition value of planning units (the value of what is in the unit). This direct connection to the original input data facilitates transparency.
- Feed these values into the connectivity analysis described earlier, and combine with a contiguity analysis which is based on the proximity of the planning unit to existing

conservation areas. There are many other analyses that could go into the spatial context value, including species specific connectivity analyses.
- Combine composition and spatial context values, divide these by a cost overlay, and do this for each objective under consideration.
- Assume the highest-rated planning unit of all the conservation objectives under consideration is allocated to that action and re-run the analysis. (After the alloction, some of the values will have changed.) This iterative allocation cycle builds solution sets iteratively up to a budget or area target (e.g., 30% of the area), mimicking the roll-out of conservation actions over time. iterative allocation cycle It also results in solution sets for multiple objectives.

There are many merits of multi-attribute overlay, including its intuitive simplicity [72], its facilitation of consensus building [22,73], and its ease in examining the sensitivity of weights [74]. However, in the past, this approach was not used in Classic SCP, mostly because it did not obviously lend itself to the representation problem as it was originally defined by the Gap Analysis Project and others. However, with the application of marginal value functions (described earlier) and the iterative allocation cycle, it is now feasible to address representation in the multi-attribute overlay. After each planning unit is selected in the heuristic, then the marginal value of each habitat type in that unit descends incrementally in its corresponding MVF curve.

Applying multi-attribute overlay to SCP also has challenges, such as putting "apples and oranges" into a common currency before comparing them, a bias against locations that have a high variance of input criteria values, and subjectivity in defining weights [75]. However, the science of multi-criteria analysis for GIS has broadened [76], and there is now a series of practices that can help mitigate these types of concerns. One such practice is the mid-value approach to transform the relative valuations of different counts of "apples" and "oranges" into matching scales before they are combined [77]. Further, to focus limited time, the particular outputs decision-makers should examine closely can be indicated via sensitivity analyses; attributes and parameters that do not have much influence on the final results do not need to be examined as carefully as those that are highly influential [78].

The iterative allocation cycle is likely to result in a less optimal solution set than Classic SCP. However, due to the large uncertainties, assumptions, data gaps (such as conservation opportunity), and dynamism in social systems, the optimality issue can be considered a panacea assumption that is attainable in gross simplifications, but unattainable in reality [79,80] and Chris Margules personal communication]. Further, because conservation is more about people and the choices they make than it is about biology [81], we posit that the cognitive, social, and multi-purpose merits of the multi-criteria approach outweigh any reduction in mathematical optimality. This appears to be an effective tradeoff between "knowing" and "doing" by allowing more user-useful and user-friendly conservation planning products [80] at the expense of optimality. A similar and somewhat complementary discussion of the above is in Gallo et al. 2020 [39], using the terms multi-attribute decision analysis (MADA) and multi-objective decision analysis (MODA).

In the Little Karoo implementation of the Framework, we identified two objectives

- Objective 1: Acquisition. In this case, the land is acquired (purchased) by a land trust and then donated to a government agency, who is then responsible for the proper stewardship of the land.
- Objective 2: Private Stewardship. In this case, the private landowner maintains ownership of the land and enters into an agreement to perform the proper stewardship of the land. Such agreements are often called easements or covenants, and often provide a tax incentive or other benefits to the landowner.

We first decided to run the standard "best bang for the buck" strategy outlined above, in which the solution set was the distribution of the planning unit allocation changes that had the highest estimated benefit to biodiversity within a fixed budget. However, this resulted in a vast majority of the selected planning units being an allocation change to private stewardship, which ran counter to the goals of the end-user partnership, which had an emphasis on acquisition. So we added a condition to the site-selection algorithm to select the best planning unit for *each* allocation on each iteration of the heuristic, rather than simply the single best unit regardless of allocation type (Figure 9). This resulted in a similar number of planning units for each allocation change in the solution set, and also demonstrates the flexibility of the framework as implemented.

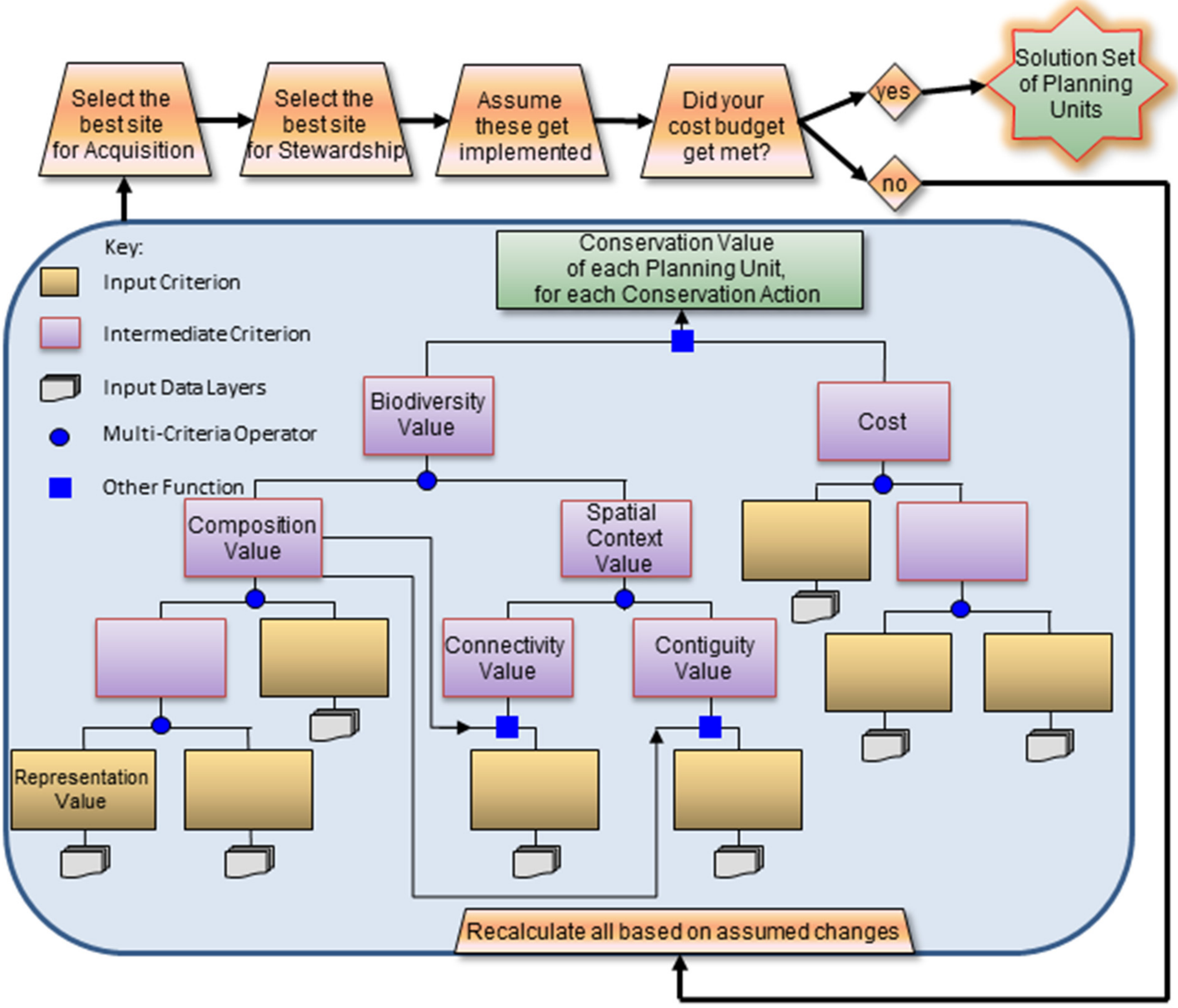

Figure 9. Simplified summary of the Earthwise SDSS for the Little Karoo, South Africa. Blank boxes represent one or many input criteria or intermediate criteria in the MCDA. Once sites are assumed to be conserved, the marginal value functions (MVFs) of the affected elements will produce new representation results, and connectivity and other spatial context values will change as well, yielding new top planning units. Note: The Little Karoo SDSS has additional useful nuances not represented in this simplified diagram, especially power-weighted division by cost, and net biodiversity value of an action (see Supplementary Materials S1: User Guide).

3.6. Strategy Five: Uncertainty Communication

Mapping the uncertainties involved in conservation science is a research priority [27,82,83], and can theoretically help meet the engagement and land-use planning challenges outlined earlier. Many stakeholders and decision-makers view scientific models with a level of mistrust, knowing that the model cannot replicate the world's complexity nor incorporate their own innate knowledge [83,84]). This mistrust is often ignored or unknown to scientists [83]. However, acknowledging and mapping the uncertainties of a model not only improves its honesty [85], which can build trust, but also helps end-users understand which results are more reliable, allowing for more informed decisions [85–88]. Indeed, in some cases, making decisions without uncertainty information is misleading and leads to biodiversity loss (e.g., [88]). Finally, strategically mapping uncertainty may help defuse contentious stakeholder processes [89].

There are many different uncertainties in conservation planning [90], and it is not financially feasible to map even more than a small subset. Further, there can be negative consequences to mapping uncertainty. It can slow down or muddle a process by allowing for people who favor the status-quo to call for inaction until the uncertainty is "solved" [91–93]. Similarly, people who disagree with the findings can try to use the uncertainty as a means of discrediting the science [91–93]. Finally, it may cause the target audience to hesitate, and feel like there is enough uncertainty to merit using their business as usual approach to decision making rather than learning and understanding the new approach presented [91–93]. Hence, careful attention should be directed towards choosing if and what type of uncertainty to quantify and map, and how to communicate it effectively [89].

A robust uncertainty analysis was beyond the scope of this research. However, we did a basic sensitivity analysis of parametric uncertainty to illustrate how even a simple "stability analysis" [90] can yield informative results. We ran the model many times, each time making a single perturbation of one of the parameter values of the Standard Run. We perturbed seven parameters associated with large or contentious assumptions, exploring a range of values that were under discussion by the science advisors, stakeholders, or in the literature. For each parameter perturbed, we did one run with a value higher than that of the standard run, and a value lower. The number of individual planning units selected for each run that differed in comparison to those of the standard run indicated the influence of that particular assumption. We then tallied the number of times each planning unit was selected in the fifteen runs (which includes the Standard Run).

4. Results

4.1. Results of Strategy One: Open Science

We released all the project input data and results along with the open-access model on the Github open science platform. We used "relative paths" in the model to allow quick integration to other end-user systems, provided a user-guide, and offer the "issues" feature of the platform to allow an online forum for end-users to ask and answer questions, or discuss issues. Further, Earthwise-LK toolbox (predominantly built with modelbuilder in ArcGIS 10.0) is modular, allowing end users to just harvest specific sub-models (Figure 10). The model is released along with a link to the input data [94]. Analysts at the Islands Trust, British Columbia did this harvesting, and converted much of the modelbuilder code into arcpy python code and wrapped it in modelbuilder tools [95] (Figure 10). There is much more to explore in this realm of collaborative science.

4.2. Results of Strategy Two: Marginal Value Functions

The Little Karoo case study involved a land trust with funds to acquire properties and donate them to a government agency, who would then manage them. Hence, a big role of the SDSS was to provide a consensus building platform as well as decision support. (Details of the case study are provided in Papers 1 and 4 of Supplementary Materials S3: Unpublished Drafts). After that study, we have continued to develop the SDSS and add new parameters. All of these parameters of Earthwise-LKand their default values are provided in Supplementary Materials S1: User Guide. The habitat targets were determined in a previous study (Supplementary Materials S4: Metadata). The other default parameter values were determined at two local expert workshops, or, for parameters created post-workshop, based on the workshop audio recordings, follow-up discussions, or our interpretation of the relevant literature. Because of this and the fact that more current and accurate data are now available, the products presented here should not be used as decision support for regional end-users. Running the model with these values resulted in the Standard Run results.

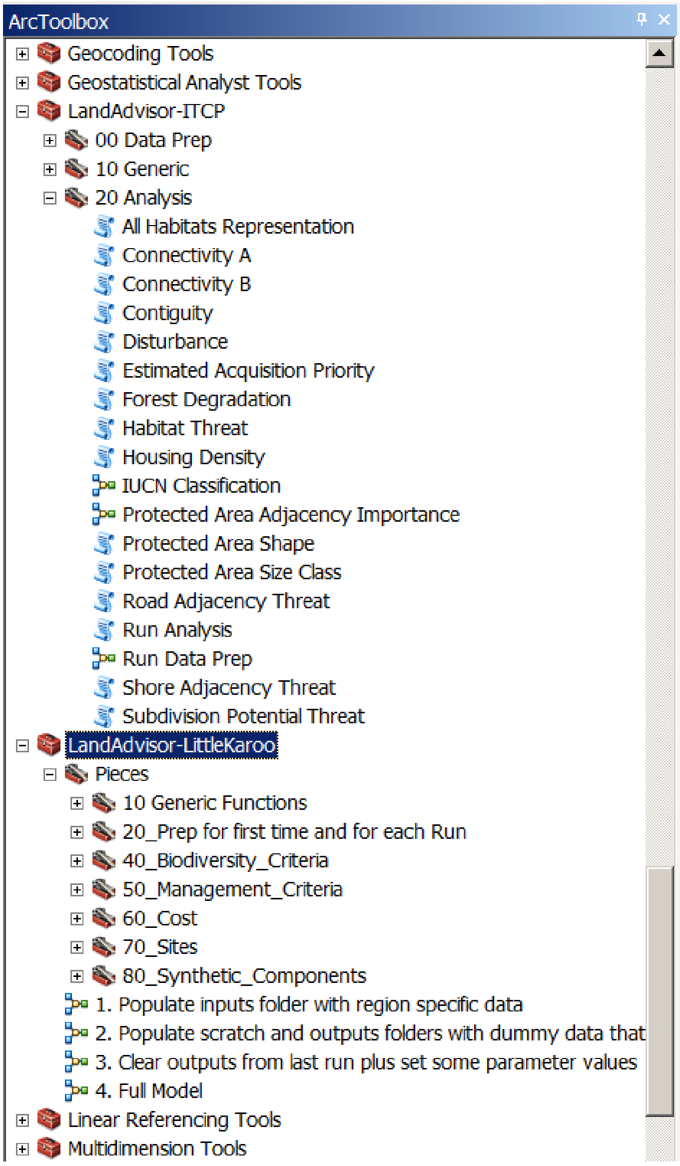

Figure 10. Two past Earthwise toolboxes in ArcGIS. Earthwise was originally called LandAdvisor. Here, the **Earthwise-LK** (LandAdvisor-LittleKaroo) Toolbox is comprised of sub-toolboxes and models as well as synthetic models that pull together all of the pieces. Clicking on a + expands the toolbox to display sub-toolboxes and models. Models can then be run, or viewed to see every methodological detail. Earthwise-ITCP (LandAdvisor-ITCP) of the Islands Trust of British Columbia, is a python-based version with more vector based processing, and also released open access, with sample data.

The input layers and parameter values of the Standard Run yielded the initial habitat representation values depicted in Figure 11. Habitats of highest representation value (Figure 11E) usually had low degrees of protection (Figure 11A,B), high levels of naturalness (Figure 11A,C) and a high habitat target threshold (Figure 11A,D). Again, MVFs can be used for other elements as well. In the case study we also implemented MVFs for species, with listing rank having a strong influence on the curve shape (Supporting Information S4: Unpublished Drafts, Paper 3, and other Supplementary Material available upon request).

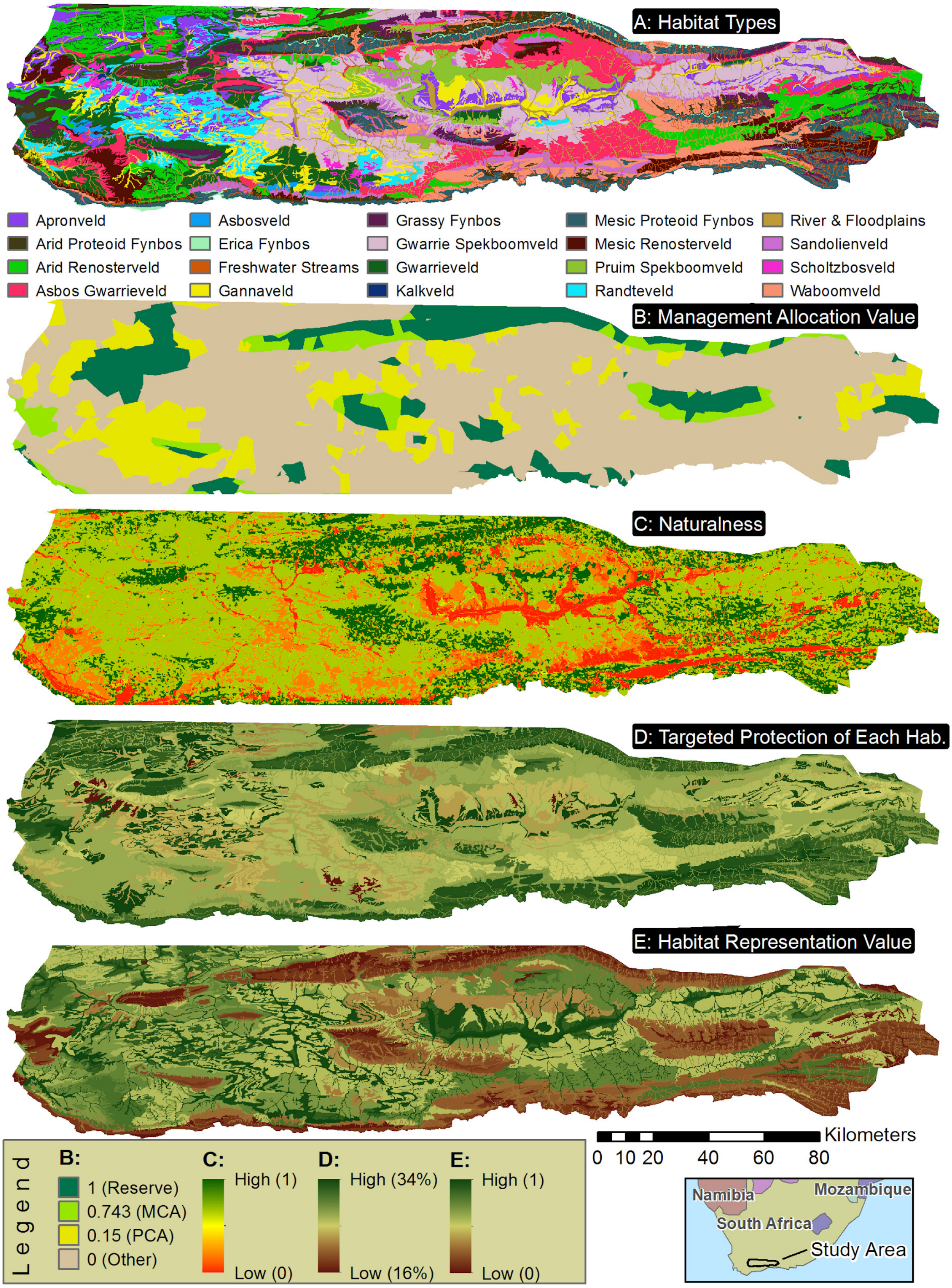

Figure 11. Input data and first iteration outputs for habitat representation. High representation value for a location indicates a high conservation priority for this criterion. Target values were determined in a previous study based on species richness estimates (see Metadata in Supplementary Information). MCA = Mountain Catchment Area, a multi-use land protection. PCA = Private Conservation Area, i.e., a pre-existing privately owned stewardship area.

4.3. Results of Strategy Three: Automated and Integrated Connectivity Modeling

The connectivity analysis worked as we hoped, running automatically for the entire region, and indicating not only where the linkages were on the landscape, but also prioritizing among them (Figure 12).

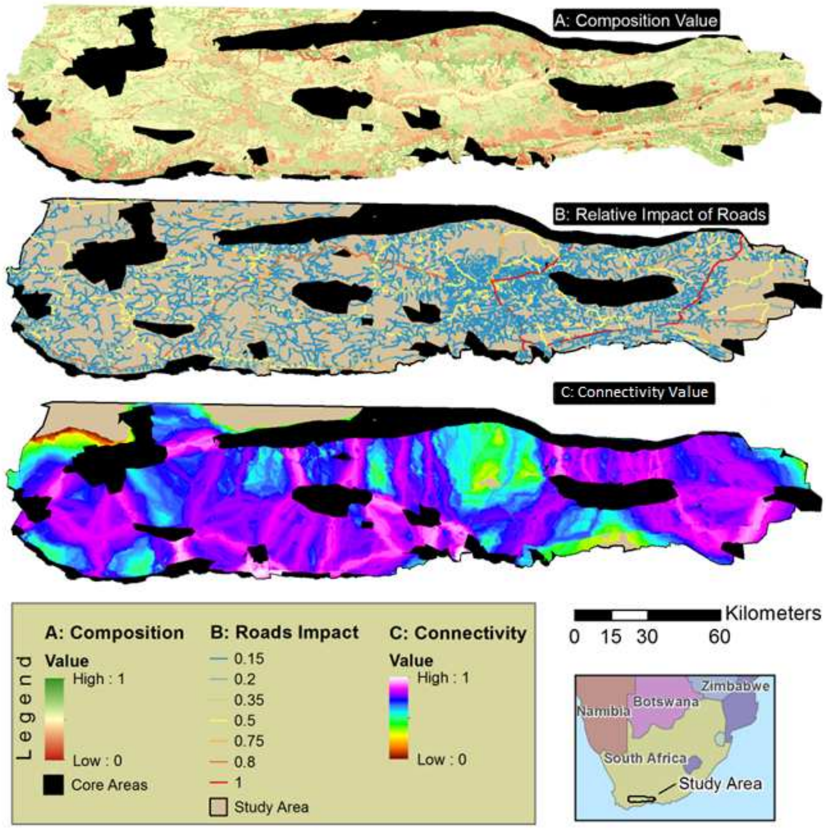

Figure 12. Key input layers and output for the Connectivity Analysis. Note: The connectivity value displayed in the third map down is for the first iteration of the heuristic. It changes as more planning units are added to the solution set. Note also how some linkages mapped as higher priority have broader swaths of white.

4.4. Results of Strategy Four: Innovations in Multi-Criteria Decision Analysis

A model run with one particular set of parameters produced a full suite of GIS layers that provided decision support. There was a raster layer for every box of the MCDA (e.g., Figure 9). Further, there was a shapefile output that includes all the planning units of the region. Each row of the shapefile table corresponds to a planning unit, and there are dozens of columns, including the mean value of each raster layer (criterion) for that particular planning unit. This allows the end user to make maps of some or all of the planning units color coded by any criterion of interest, thereby displaying results at two levels of resolution. This provides extra transparency to the user; they can see all the cell values of a particular planning unit to determine why it received such a surprisingly high (or low) value for a particular criterion, and where in the planning unit those high and low values are. This could help in bridging between SCP and adaptive management of individual properties.

The Earthwise-LK results illustrate several benefits of having the MVFs, MCDA, and connectivity modeling all analyzed in the high resolution of 100 m cells rather than at the parcel resolution. When looking at particular planning units and why they were included (or excluded) from the solution set, the stakeholders really appreciated being able to see the spatial distribution of any criterion, at a 100 m resolution, within the planning unit and surroundings. In fact, it was one of these intermediate raster layers that became the favorite decision support tool of the stakeholders [96].

With ArcGIS 9.3 and Windows 7 on a typical workstation, it was not possible to utilize the vector based format of the previous Earthwise applications but at such a high resolution. Hence, we reprogrammed it all into the raster environment using Map Algebra. This worked, but was slow. This would have been improved for some of the calculations such as the marginal value curves, by exporting to a table environment, such as vector analysis and calculating aspatially. It also had drawbacks of requiring more disk space requirements, and managing hundreds of output files rather than just one or a few with many fields. These problems would likely have magnified if we tried to put the outputs into a user-friendly and useful web viewer rather than just providing hardcopy maps.

4.5. Results of Strategy Five: Uncertainty Communication

We mapped the results of the sensitivity analysis (Figure 13). See the User Guide (Supplementary Materials S1) for further details about the parameter stability methods and results.

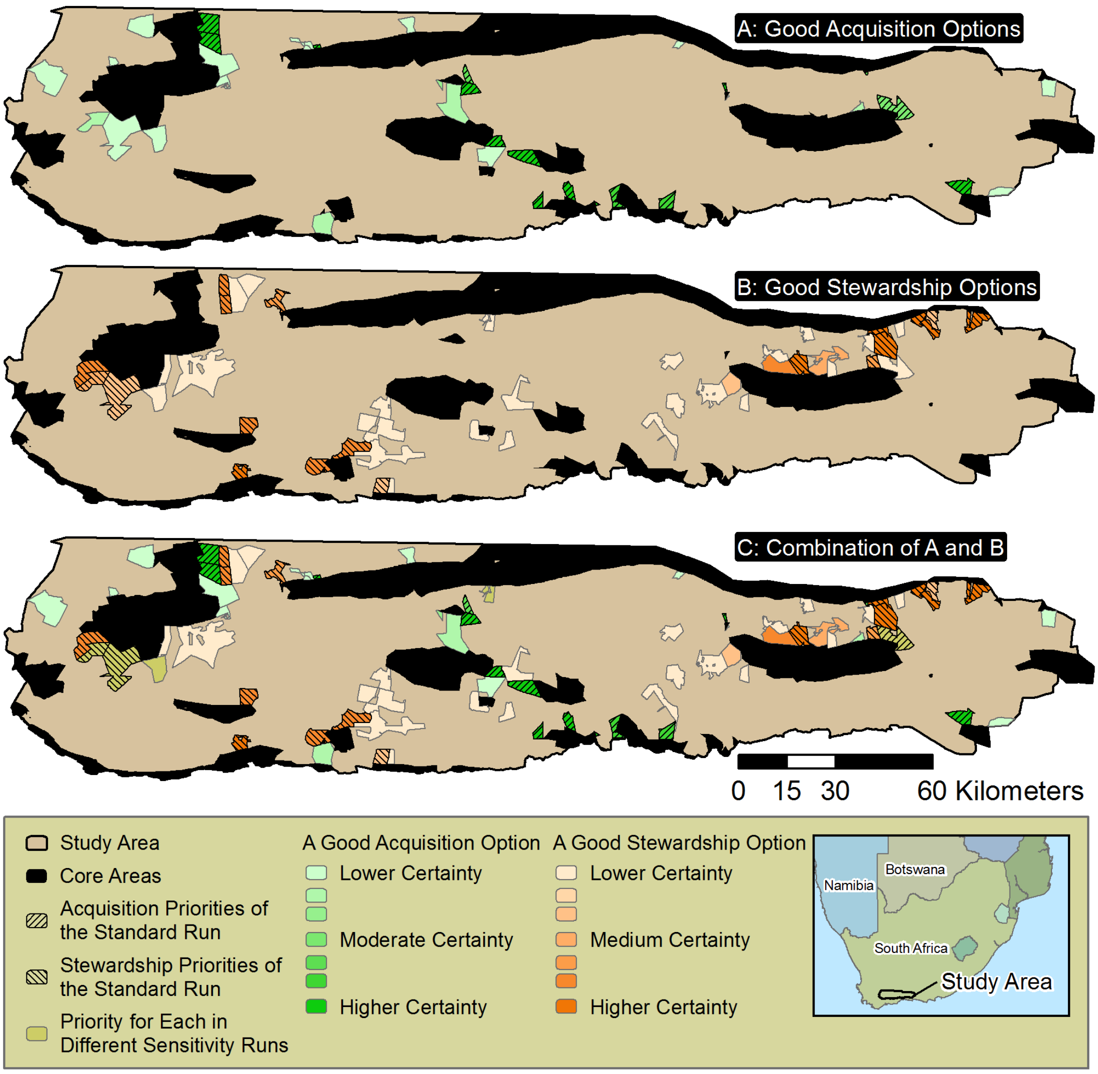

Figure 13. Good acquisition and stewardship options, with an indication of some uncertainty. The small units with black boundaries are priorities of the Standard Run. Not also that the term "Higher Certainty" was used instead of "High Certainty".

5. Discussion

The design choices of the spatial decision support system and its surrounding social process that support collaborative conservation planning and action have profound influence on success, but are relatively overlooked. In the above Methods and Results sections, we discussed and illustrated five strategies for addressing four major challenges in closing the gaps between conservation assessment, planning, and implementation (summarized in Table 1). We also posit that the strategies also address an overarching problem: that society is becoming increasingly disconnected from nature.

Observations of how the 30 × 30 global initiative is starting to play out in politics, and in science (e.g., [3,4,97–99]), are that there is an order of magnitude more stakeholders and decision-makers involved in any given conservation planning effort compared to efforts in the past several decades when government mandates for SCP were rare. As the number of stakeholders and decision-makers increases so too does the number and complexity of the social interactions. Hence, it is likely that the human elements affecting how conservation planning leads to on–the-ground implementation will become increasingly important. The findings and recommendations of this paper intersect with this social science. While originally drafted without 30 × 30 in mind, they have become increasingly apropos.

In addition to all the observed and expected benefits of the Earthwise Framework in engaging stakeholders and end-users in a 30 × 30 process, it also has great potential in providing an analytic frame for the challenge of including other effective area-based conservation measures (OECMs) in the 30 × 30 process. OECMs are not typical protected areas, but are areas already delivering effective biodiversity long term, such as Indigenous and Community Conserved Areas (ICCAs) [100] and Private Protected Areas (PPAs). They also include certain government lands managed for natural resource extraction as much or more than biodiversity conservation, but that do offer long term conservation of important biodiversity. We make the argument that they can apply to 30 by 30, but not as much as protected areas. Applying the principle of moving beyond binary characterization in the manner presented here in the Little Karoo could be a way of operationalizing this (e.g., management quality-weighted area of Figure 8). In other words, if an OECM of a certain type could require 10 units of area to achieve the equivalent of 1 unit of protected area. (The actual ratio should be determined by a transparent and inclusive consensus-based process.) This would count accordingly towards representation targets, as well as towards the overarching 30% protected area target. Different OECM types could have different quality weighted areas. Further, the iterative allocation cycle does not need to select one protected area and then one OECM in each iteration as we did in the Little Karoo. It can be programmed to instead pick the one PA or OECM that had the highest benefit/cost ratio during each iteration. Or, some balanced blend between the two extremes could be employed. Further, management effectiveness and/or naturalness metrics, if fairly gathered across the region such as with remote sensing and verified citizen science observation, can also be incorporated. In order to incentivize the creation of additional protected areas in regions that attain 30% via the use of OECMs, the calculated quality weighted area of any newly added OECM could be programmed to decrease in an agreed upon rate as time passes.

SCP has an unmet potential to effectively bridge across spatial and jurisdictional scales. Such a bridge would allow the leveraging of the best aspects of finer scale SCP and coarse scale SCP. Finer scale SCP, such as at the landscape scale like the Little Karoo or Sierra Nevada Mountains (~10–500 thousand km^2), better allows the convening of affected stakeholders, incorporating nuances of local ecology, and for strategy design and implementation [7]. Coarser scale SCP, such as for all of a large region like South Africa, China or the European Union (~0.5–20 million km^2), is able to leverage economies of scale, using datasets consistent across the region and inclusion of high-level decision makers with adequate authority. The Earthwise Framework has the potential to provide that bridge, given its multicriteria overlay foundation, and the assumption that it is easier for more people to understand than existing frameworks. For example, if the framework were applied to all of the landscapes of a region, and also the region itself, then the spatial outputs from the landscapes can be an input criterion to the regional overlay analysis, and vice versa. (The model runs to develop these inputs would be with the other scale weighted at 0 to avoid double counting.) The products would then have a good chance at having shared ownership and buy-in from the multiple scales of players. Additionally, the process of weighting the priorities from each scale could be a mechanism for structuring the dialogues between institutions at multiple scales of jurisdiction and management (e.g., strategies and plans) that are often necessary for solving particularly challenging problems [50]. This could become especially important with the 30 × 30 initiative because there are efforts to do conservation planning for the whole earth, for continents, regions, and landscapes, including the typical country/state/county siloes. Implementing such a framework could have all these complement rather than contradict each other.

The framework described and illustrated can be implemented in a variety of ways, and built with different software tools. For example, the framework recommends a connectivity algorithm or tool that can not only prioritize within a linkage, but among them as well, and to do this for an entire region with one command rather than requiring a linkage by linkage analysis and combination. In Earthwise-LK, we did this with an arcpy script. Subsequently, we collaborated with Brad McRae to program these abilities into Linkage Mapper [60], and then used this as part of a different Earthwise instance [39]. Initial indications are that the Little Karoo connectivity algorithm performs better in assigning a connectivity value to every reporting unit on the landscape, but is slower to run and is less helpful for stand-alone connectivity analyses. Better developing and/or evaluating the tools has research merits.

Similarly, there is much room for improvement in the graphical user interface (ArcMap) in the Little Karoo effort used by analysts and stakeholders for interacting with the model methods and results. Fortunately, subsequent iterations of Earthwise SDSS in other regions addressed this by embedding the Environmental Evaluation Modeling System (EEMS) into the SDSS [39]. EEMS is software designed for building, performing, and viewing multi-criteria combinations, and has the option of using marginal value curves to normalize criteria (along with many other normalization options in the library) [101]. It is part of the Modelers Python Implemented Library of Tools (MPILOT), an extensible, plugin-based python framework [102]. Hence, it is suitable for the iterative allocation cycle used in the Earthwise Framework. Further, the latest version of EEMS addresses the vector vs. raster quandary discussed earlier by allowing the users to make very high resolution vector reporting unit datasets, which are then converted to CSV filess and analyzed outside of ArcGIS then rejoined to display results. This yields the benefits of vector, such as using parcels or subwatersheds as reporting units (i.e., sites) and avoiding the need for map algebra of rasters, but also attaining fast processing speeds. EEMS currently has two different graphical user interfaces for viewing the logic model tree, and how each criterion or reporting unit maps out. One of these can be embedded into custom web apps created by third parties. We explored the EEMS approach in a related study [39] and found the processing time for calculating representation value to be improved about tenfold, and the ease in defining the marginal value curves greatly enhanced. Hence, in future applications, it is advisable to use EEMS or some similar open source code for combining criteria, as opposed to the code and models created from scratch for the Little Karoo effort.

Because most components of the six known Earthwise Framework applications [38,39] are modular, in developing the next application, it may be best to pick and choose from the existing modules of python, visual basic, EEMS, and modelbuilder code rather than just building off of one of them. Alternatively, it may be best to convert the most recent application, LandAdvisor-SN [39], from a python-EEMS-arcpy-modelbuilder hybrid to one that avoids native modelbuilder scripting.

If there is a need to further differentiate the MVFs among habitats and lessen the need for targets (i.e., to adopt curves in the shape of "Low emphasis in target achievement" in Figure 6), other factors such as projected loss of habitat type [38] and species richness of a habitat type [103] can be integrated into defining the shape of the MVF for each habitat. This could be done in a similar manner as historical loss here (e.g., Figure 8).

However, there is a tradeoff with this level of precision. This approach of modifying the shapes of each habitat's MVF based on these auxiliary factors is not especially transparent (it takes time to find out why a particular habitat is valued at a certain level), and doing the above would make it even more opaque. In a follow-up study we experimented with moving these factors, such as designation-weighted area (essentially the same as quality weighted area) out of the MVF and instead combining them into the SDSS as individual criteria that can be affected via weighted sums [39]. It appears that the ease-of-use benefits of this approach may outweigh the benefit of highly differentiated and variable MVFs among habitat types. That said, the approach outlined here yields MVFs that can be stand-alone graphical representations to the state of a particular representation element (e.g., habitat) type. This tradeoff might merit further evaluation or corroboration.

AI was mentioned in the collaborative conservation planning and action subheading of Strategy one. It was not to state that there is no role for AI in the Earthwise Framework. Now, and especially in the future, ethically grounded AI can be utilized in partnership with experts and stakeholders in opining about the code and parameters used, and like the humans present, this opinion gets accounted for in making the final model and outputs. Extra or less weight can be given to the AI contribution, similar as to how extra weight can be given to experts [96]. AI is more efficient than DDI learning to solve a problem, like beating the world's grand master at chess, but it is less transparent. AI can also play a role in gathering and sharing aspatial information in the Earthwise Framework via knowledge networks or knowledge graphs. These are becoming ubiquitous in the business world, and building them at regional scales for communities wanting to become more sustainable has large potential [104].

If a living SDSS is developed for a region such that new input data are quickly and easily reflected in SDSS outputs via automated data processing, this could increase motivation of citizen scientists, institutions, and funders to make monitoring a certainty rather than a luxury or afterthought. This could help with a blooming of citizen science, which can lead to a larger percentage of people spending time in and observing nature, thereby helping heal our growing disconnect with nature. Further, citizen science, especially that which leverages people's affinity for their home region, has the potential of recruiting participants in the broader environmental protection process [105].

One of the characteristics of open science is to experiment with new ways of furthering discourse that were not possible before the internet age even though they may be counter to convention [41]. What are SDSS development and sharing protocols that can facilitate interoperability and easily updated systems? We agree that data collection and preprocessing take about 80% of an assessment [106], so suggest that a "best practice" could be to save (and share with other regions) pre-processing steps in models/scripts to enable continuity and adaptive planning. What could be done to incentivize this and to lower the barriers to this practice?

Finally, there are now at least six case studies that have explored this framework [38,39,96] but there is no single reference for tightly communicating the Earthwise Framework, nor how to apply it. This is needed as well as an evaluation, in comparison with alternate frameworks (e.g., MARXAN with Zones, and Zonation), in not only mathematical optimality, the iterative allocation algorithm's theoretical weakness, but also its strengths including the breadth of ways for stakeholders and end-users to understand a part of the framework in which they can then engage, and the ability to positively affect rates of conservation plan implementation, monitoring, and updating. In such an evaluation, the similarities between the iterative allocation cycle and the iterative planning process can be further elaborated upon.

Conclusions

Using an open science design allows a greater number of decision-makers, stakeholders, and citizens to participate in SCP. Increased participation leads to increased understanding and empathy, which builds resolve and follow-through for the tough trade-offs and commitments that need to be made in order to implement conservation plans. Increased participation can come in the form of citizen science data provision, accessing and commenting upon spatial information, providing data, opining about model weights, or nominating and voting upon criteria to be included in the next round of analysis in an SDSS.

Critical enabling factors for this new approach is to design the SDSS to facilitate this participation, and so it is living. This keeps the SDSS relevant amid an ever changing landscape and culturescape. As climate change progresses these changes will likely accelerate and take unexpected directions as society tries to adapt (e.g., coastal populations migrating inland). Further, people can engage in one of many ways with the living SDSS, knowing that their contribution will be included in future iterations. Having an SDSS that is living allows planning teams to allocate less time to conservation assessment over the years and more to the sticky but critical social aspects of planning, implementation, and monitoring. To make the SDSS living, as many steps as possible within and among the stages of the SDSS need to be automated. We detailed two designs and a framework that further automate conservation assessment. MVFs allow for a continuous and real-time approach to representation that does not require initial or re-negotiation of target thresholds. Automated connectivity modeling using landscape permeability recalculates linkage locations as data and conditions change, and also prioritizes among linkages. Both of these can be combined in an automated workflow using MCDA innovations that provides solution sets as well as real-time valuation of any particular planning unit. Finally, we suggest that communicating uncertainty, despite potentially negative consequences discussed earlier, helps guide future SDSS development while maintaining trust and allowing people to best leverage data-driven intelligence and human intelligence in making decisions. The suggestions in this paper and their implications are broad and may seem unattainable for any given project scope, but by embracing the principles of open science we can collaborate and share in ways only recently possible to attain surprising progress.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12010254/s1. Supplementary Materials S1: User Guide. Earthwise-LK 3.2.3 beta. Supplementary Materials S2: Calibrating the Marginal Value Functions—Habitats. Supplementary Materials S3: Unpublished Drafts. Four Drafts Pertaining to Collaborative Conservation Planning and Action. Supplementary Materials S4: Metadata for Earthwise-LKv3.2 Sample Data. As mentioned earlier, the model, data and code are available online: https://github.com/EarthwiseFramework/Earthwise-LK (accessed on 1 October 2022).

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References

1. Leakey, R.E.; Lewin, R. *The Sixth Extinction: Patterns of Life and the Future of Humankind*; Anchor Books: New York, NY, USA, 1996; p. 271.
2. Almond, R.E.A.; Grooten, M.D.; Bignoli, J.; Petersen, T. *Living Planet Report 2022–Building a Nature-Positive Society*; WWF: Gland, Switzerland, 2022.
3. Ainsworth, D.; Collins, T.; d'Amico, F. Nations Adopt Four Goals, 23 Targets for 2030 In Landmark UN Biodiversity Agreement. Convention on Biological Diversity December 19. 2022, Press Release. Available online: https://prod.drupal.www.infra.cbd.int/sites/default/files/2022-12/221219-CBD-PressRelease-COP15-Final_0.pdf (accessed on 1 October 2022).
4. Waldron, A.; Adams, V.; Allan, J.; Arnell, A.; Asner, G.; Atkinson, S.; Baccini, A.; Baillie, J.; Balmford, A.; Beau, J.A.; et al. *Protecting 30% of the Planet for Nature: Costs, Benefits and Economic Implications*; University of Cambridge: Cambridge, UK, 2020; Available online: https://www.conservation.cam.ac.uk/files/waldron_report_30_by_30_publish.pdf. (accessed on 1 October 2022).
5. Margules, C.; Pressey, R. Systematic Conservation Planning. *Nature* **2000**, *405*, 243–253. [CrossRef] [PubMed]
6. Knight, A.; Cowling, R.; Campbell, B. An operational model for implementing conservation action. *Conserv. Biol.* **2006**, *20*, 408–419. [CrossRef] [PubMed]
7. Campellone, R.M.; Chouinard, K.M.; Fisichelli, N.A.; Gallo, J.A.; Lujan, J.R.; McCormick, R.J.; Miewald, T.A.; Murry, B.A.; Pierce, D.J.; Shively, D.R. The iCASS Platform: Nine Principles for Landscape Conservation Design. *Landsc. Urban Plan.* **2018**, *176*, 64–74. [CrossRef]
8. Adams, V.M.; Mills, M.; Weeks, R.; Segan, D.B.; Pressey, R.L.; Gurney, G.G.; Groves, C.; Davis, F.W.; Álvarez-Romero, J.G. Implementation Strategies for Systematic Conservation Planning. *Ambio* **2018**, *48*, 139–152. [CrossRef] [PubMed]
9. Prendergast, J.R.; Quinn, R.M.; Lawton, J.H. The Gaps between Theory and Practice in Selecting Nature Reserves. *Conserv. Biol.* **1999**, *13*, 484–492. [CrossRef]
10. Knight, A.; Cowling, R.; Rouget, M.; Balmford, A.; Lombard, A.; Campbell, B. "Knowing" But Not "Doing": Selecting Priority Conservation Areas and the Research-Implementation Gap. *Conserv. Biol.* **2008**, *22*, 610–617. [CrossRef]
11. Reyers, B.; Roux, D.J.; Cowling, R.M.; Ginsberg, A.E.; Nel, J.L.; O'Farrell, P. Conservation Planning as a Transdisciplinary Process. *Conserv. Biol.* **2010**, *24*, 957–965. [CrossRef]
12. Pressey, R.L.; Mills, M.; Weeks, R.; Day, J.C. The plan of the day: Managing the dynamic transition from regional conservation designs to local conservation actions. *Biol. Conserv.* **2013**, *166*, 155–169. [CrossRef]
13. Balmford, A. Conservation Planning in the Real World: South Africa Shows the Way. *Trends Ecol. Evol.* **2003**, *18*, 435–438. [CrossRef]
14. Knight, A.T.; Driver, A.; Cowling, R.M.; Maze, K.; Desmet, P.G.; Lombard, A.T.; Rouget, M.; Botha, M.A.; Boshoff, A.F.; Castley, J.G.; et al. Designing systematic conservation assessments that promote effective implementation: Best practice from South Africa. *Conserv. Biol.* **2006**, *20*, 739–750. [CrossRef]
15. Lombard, A.T.; Cowling, R.M.; Vlok, J.H.J.; Fabricius, C. Designing Conservation Corridors in Production Landscapes: Assessment Methods, Implementation Issues, and Lessons Learned. *Ecol. Soc.* **2010**, *15*, art7.
16. Moilanen, A.; Wilson, K.; Possingham, H. *Spatial Conservation Prioritization: Quantitative Methods and Computational Tools*; Oxford University Press: Oxford, UK, 2009; p. 304.
17. Arnstein, S.R. A Ladder Of Citizen Participation. *J. Am. Inst. Plan.* **1969**, *35*, 216–224. [CrossRef]
18. Willard, T. *Dating the Decision-Makers: Moving from Communications to Engagement*; Version 1.1; International Institute for Sustainable Development: Winnipeg, MN, Canada, 2001.
19. Rivers, N.; Truter, H.J.; Strand, M.; Jay, S.; Portman, M.; Lombard, A.T.; Amir, D.; Boyd, A.; Brown, R.L.; Cawthra, H.C.; et al. Shared visions for marine spatial: Insights from Israel, South Africa, and the United Kingdom. *Ocean Coast. Manag.* **2022**, *220*, 106069. [CrossRef]
20. Armitage, D.; Marschke, M.; Plummer, R. Adaptive co-management and the paradox of learning. *Glob. Environ. Change* **2008**, *18*, 86–98. [CrossRef]
21. Cowling, R.; Egoh, B.; Knight, A.; O'Farrell, P.; Reyers, B.; Rouget, M.; Roux, D.; Welz, A.; Wilhelm-Rechman, A. An operational model for mainstreaming ecosystem services for implementation. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 9483–9488. [CrossRef]
22. Theobald, D.M.; Hobbs, N.T.; Bearly, T.; Zack, J.A.; Shenk, T.; Riebsame, W.E. Incorporating biological information in local land-use decision making: Designing a system for conservation planning. *Landsc. Ecol.* **2000**, *15*, 35–45. [CrossRef]
23. Pierce, S.M.; Cowling, R.M.; Knight, A.T.; Lombard, A.T.; Rouget, M.; Wolf, T. Systematic conservation planning products for land-use planning: Interpretation for implementation. *Biol. Conserv.* **2005**, *125*, 441–458. [CrossRef]
24. Gerber, J.D.; Rissman, A.R. Land-conservation strategies: The dynamic relationship between acquisition and land-use planning. *Environ. Plan. A* **2012**, *44*, 1836–1855. [CrossRef]

25. USFS. *National Forest System Land Management Planning Rule*; Department of Agriculture: Washington, DC, USA, 2012.
26. Faith, D.P.; Walker, P.A. Integrating Conservation and Development: Effective Trade-Offs between Biodiversity and Cost in the Selection of Protected Areas. *Biodivers. Conserv.* **1996**, *5*, 431–446. [CrossRef]
27. Sarkar, S.; Pressey, R.L.; Faith, D.P.; Margules, C.R.; Fuller, T.; Stoms, D.M.; Moffett, A.; Wilson, K.A.; Williams, K.J.; Williams, P.H.; et al. Biodiversity Conservation Planning Tools: Present Status and Challenges for the Future. *Annu. Rev. Environ. Resour.* **2006**, *31*, 123–159. [CrossRef]
28. Noss, R.; Carroll, C.; Wuerthner, G. A multicriteria assessment of the irreplaceability and vulnerability of sites in the Greater Yellowstone Ecosystem. *Conserv. Biol.* **2002**, *16*, 895–908. [CrossRef]
29. Faith, D.P.; Carter, G.; Cassis, G.; Ferrier, S.; Wilkie, L. Complementarity, biodiversity viability analysis, and policy-based algorithms for conservation. *Environ. Sci. Policy* **2003**, *6*, 311–328. [CrossRef]
30. Meir, E.; Andelman, S.; Possingham, H.P. Does conservation planning matter in a dynamic and uncertain world? *Ecol. Lett.* **2004**, *7*, 615–622. [CrossRef]
31. Murdoch, W.; Polasky, S.; Wilson, K.A.; Possingham, H.P.; Kareiva, P.; Shaw, R. Maximizing Return on Investment in Conservation. *Biol. Conserv.* **2007**, *138*, 375–388. [CrossRef]
32. Haight, R.G.; Snyder, B.G.; Revelle, C.S. Metropolitan open-space protection with uncertain site availability. *Conserv. Biol.* **2005**, *19*, 327–337. [CrossRef]
33. Heller, N.; Zavaleta, E. Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biol. Conserv.* **2009**, *142*, 14–32. [CrossRef]
34. Steinitz, C.F. A framework for Theory Applicable to the Education of Landscape Architects (and Other Environmental Design Professionals). *Landsc. J.* **1990**, *9*, 136–143. [CrossRef]
35. Steinitz, C. *A Framework for Geodesign: Changing Geography by Design*; Esri Press: Redlands, CA, USA, 2012; p. 224.
36. CMP Open Standards for the Practice of Conservation: Version 4.0; Drafted by The Conservation Measures Partnership. 2020. Available online: https://conservationstandards.org/wp-content/uploads/sites/3/2020/10/CMP-Open-Standards-for-the-Practice-of-Conservation-v4.0.pdf (accessed on 1 October 2022).
37. Burley, F.W. Monitoring Biological Diversity for Setting Priorities in Conservation. In *Biodiversity*; Wilson, E.O., Ed.; National Academy Press: Washington, DC, USA, 1988; pp. 227–230.
38. Davis, F.; Costello, C.; Stoms, D. Efficient conservation in a utility-maximization framework. *Ecol. Soc.* **2006**, *11*, 33. [CrossRef]
39. Gallo, J.A.; Aplet, G.; Greene, R.; Thomson, J.; Lombard, A. A Transparent and Intuitive Modeling Framework and Software for Efficient Land Allocation. *Land* **2020**, *9*, 444. [CrossRef]
40. Tapscott, D.; Williams, A. *Wikinomics: How Mass Collaboration Changes Everything Second*; Penguin Group: New York, NY, USA, 2008.
41. Nielsen, M. *Reinventing Discovery: The New Era of Networked Science*; Princeton University Press: Princeton, NJ, USA, 2011; p. 280.
42. Shirk, J.L.; Ballard, H.L.; Wilderman, C.C.; Phillips, T.; Wiggins, A.; Jordan, R.; McCallie, E.; Minarchek, M.; Lewenstein, B.V.; Krasny, M.E.; et al. Public Participation in Scientific Research: A Framework for Deliberate Design. *Ecol. Soc.* **2012**, *17*, 20. [CrossRef]
43. Dickinson, J.L.; Shirk, J.; Bonter, D.; Bonney, R.; Crain, R.L.; Martin, J.; Phillips, T.; Purcell, K. The current state of citizen science as a tool for ecological research and public engagement. *Front. Ecol. Environ.* **2012**, *10*, 291–297. [CrossRef]
44. Newman, G.; Wiggins, A.; Crall, A.; Graham, E.; Newman, S.; Crowston, K. The future of citizen science: Emerging technologies and shifting paradigms. *Front. Ecol. Environ.* **2012**, *10*, 298–304. [CrossRef]
45. Bowman, K.; Rugg, A.; Marsico, J. *Polls on the Environment, Energy, Global Warming, and Nuclear Power*; AEI: Washington, DC, USA, 2013; p. 143.
46. Haywood, B.K. A "Sense of Place" in Public Participation in Scientific Research. *Sci. Educ.* **2014**, *98*, 64–83. [CrossRef]
47. Chun, S.A.; Shulman, S.; Sandoval, R.; Hovy, E. Government 2.0: Making connections between citizens, data and government. *Inf. Polity* **2010**, *15*, 1–9. [CrossRef]
48. Lathrop, D.; Ruma, L. Open Government: Collaboration, Transparency, and Participation in Practice. Page 402. 2010. Available online: http://www.amazon.com/Open-Government-Collaboration-Transparency-Participation/dp/0596804350 (accessed on 8 May 2014).
49. O'Reilly, T. Government as a Platform. *Innov. Technol. Gov. Glob.* **2011**, *6*, 13–40. [CrossRef]
50. Cash, D.W.; Adger, W.; Berkes, F.; Garden, P.; Lebel, L.; Olsson, P.; Pritchard, L.; Young, O. Scale and cross-scale dynamics: Governance and information in a multilevel world. *Ecol. Soc.* **2006**, *11*, 8. [CrossRef]
51. Jarvis, R.M.; Borrelle, S.B.; Forsdick, N.J.; Pérez-Hämmerle, K.-V.; Dubois, N.S.; Griffin, S.R.; Recalde-Salas, A.; Buschke, F.; Rose, D.C.; Archibald, C.L.; et al. Navigating Spaces between Conservation Research and Practice: Are We Making Progress? *Ecol. Solut. Evid.* **2020**, *1*, 12028. [CrossRef]
52. Moilanen, A. Landscape Zonation, benefit functions and target-based planning: Unifying reserve selection strategies. *Biol. Conserv.* **2007**, *134*, 571–579. [CrossRef]
53. Wilson, K.A.; Underwood, E.C.; Morrison, S.A.; Klausmeyer, K.R.; Murdoch, W.W.; Reyers, B.; Wardell-Johnson, G.; Marquet, P.A.; Rundel, P.W.; McBride, M.F.; et al. Conserving Biodiversity Efficiently: What to Do, Where, and When. *PLoS Biol.* **2007**, *5*, e223. [CrossRef]

54. Beier, P.; Brost, B. Use of Land Facets to Plan for Climate Change: Conserving the Arenas, Not the Actors. *Conserv. Biol.* **2010**, *24*, 701–710. [CrossRef]
55. Carwardine, J.; Klein, C.J.; Wilson, K.A.; Pressey, R.J.; Possingham, H.P. Hitting the target and missing the point: Target-based conservation planning in context. *Conserv. Lett.* **2009**, *2*, 4–11. [CrossRef]
56. Hoekstra, J.M.; Boucher, T.M.; Ricketts, T.H.; Roberts, C. Confronting a biome crisis: Global disparities of habitat loss and protection. *Ecol. Lett.* **2005**, *8*, 23–29. [CrossRef]
57. Gallo, J.A.; Pasquini, L.; Reyers, B.; Cowling, R.M. The role of private conservation areas in biodiversity representation and target achievement in the Little Karoo, South Africa. *Biol. Conserv.* **2009**, *142*, 446–454. [CrossRef]
58. Soule, M.E.; Terborgh, J. *Continental Conservation: Scientific Foundations of Regional Reserve Networks*; Island Press: Washington, DC, USA, 1999; pp. xi, 227. ISBN 9781559636971.
59. Nuñez, T.A.; Lawler, J.J.; McRae, B.H.; Pierce, D.J.; Krosby, M.B.; Kavanagh, D.M.; Singleton, P.H.; Tewksbury, J.J. Connectivity Planning to Address Climate Change. *Conserv. Biol.* **2013**, *27*, 407–416. [CrossRef] [PubMed]
60. Gallo, J.A.; Greene, R. *Connectivity Analysis Software for Estimating Linkage Priority*; Conservation Biology Institute: Corvallis, OR, USA, 2018. [CrossRef]
61. Beier, P.; Majka, D. Designing Wildlife Corridors with ArcGIS. 2007. Available online: http://www.corridordesign.org (accessed on 10 January 2014).
62. McRae, B.; Dickson, B.; Keitt, T.; Shah, V. Using circuit theory to model connectivity in ecology and conservation. *Ecology* **2008**, *10*, 2712–2724. [CrossRef] [PubMed]
63. McRae, B.H.; Kavanagh, D.M. *Linkage Mapper Connectivity Analysis Software*, Version 3.0; The Nature Conservancy: Seattle, WA, USA, 2011.
64. Phillips, P.; Clark, M.M.; Baral, S.; Koen, E.L.; Bowman, J. Comparison of Methods for Estimating Omnidirectional Landscape Connectivity. *Landsc. Ecol.* **2021**, *36*, 1647–1661. [CrossRef]
65. Theobald, D.M.; Reed, S.E.; Fields, K.; Soulé, M. Connecting natural landscapes using a landscape permeability model to prioritize conservation activities in the United States. *Conserv. Lett.* **2012**, *5*, 123–133. [CrossRef]
66. Moore, G.E. Cramming more components onto integrated circuits. *Electronics* **1965**, 4. [CrossRef]
67. Spatial Decision Support Knowledge Portal. Available online: http://sdsportal.sdsconsortium.org/ (accessed on 1 October 2022).
68. Malczewski, J. *GIS and Multicriteria Decision Analysis*; John Wiley & Sons: New York, NY, USA, 1999.
69. McHarg, I.L. *Design with Nature*; Paperback. Published for American Museum of Natural History; Doubleday/Natural History Press: Garden City, NY, USA, 1971; pp. viii, 197.
70. Eastman, R.J.; Toledano, J. Raster Procedures for Multi-Criteria/Multi-Objective Decisions. *Photogramm. Eng. Remote Sens.* **1995**, *61*, 539–547.
71. Ball, I.; Possingham, H. *MARXAN V1.8.2: Marine Reserve Design Using Spatially Explicit Annealing, a Manual*; University of Queensland: St. Lucia, QL, Australia, 2000.
72. Balasubramaniam, A.; Voulvoulis, N. The Appropriateness of Multicriteria Analysis in Environmental Decision-Making Problems. *Environ. Technol.* **2005**, *26*, 951–962. [CrossRef]
73. Feick, R.; Hall, G.B. Consensus-building in a Multi-Participant Spatial Decision Support System. *URISA J.* **1999**, *11*, 17–23.
74. Malczewski, J. GIS-based multicriteria decision analysis: A survey of the literature. *Int. J. Geogr. Inf. Sci.* **2006**, *20*, 703–727. [CrossRef]
75. Wilson, K.A.; Carwardine, J.; Possingham, H.P. Setting Conservation Priorities. *Ann. N. Y. Acad. Sci.* **2009**, *1162*, 237–264. [CrossRef]
76. Greene, R.; Devillers, R.; Luther, J.E.; Eddy, B.G. GIS-Based Multiple-Criteria Decision Analysis. *Geogr. Compass* **2011**, *5*, 412–432. [CrossRef]
77. Malczewski, J. On the Use of Weighted Linear Combination Method in GIS: Common and Best Practice Approaches. *Trans. GIS* **2000**, *4*, 5. [CrossRef]
78. Feick, R.; Hall, G.B. A method for examining the spatial dimension of multi-criteria weight sensitivity. *Int. J. Geogr. Inf. Sci.* **2004**, *18*, 815–840. [CrossRef]
79. Ostrom, E.; Janssen, M.A.; Anderies, J.M. Going beyond panaceas. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 15176–15178. [CrossRef]
80. Knight, A.T.; Cowling, R.M. Trading-Off "Knowing" versus "Doing" for Effective Conservation Planning. In *Trade-Offs in Conservation*; Wiley-Blackwell: Hoboken, NJ, USA, 2010; pp. 273–291.
81. Balmford, A.; Cowling, R. Fusion or Failure? The Future of Conservation Biology. *Conserv. Biol.* **2006**, *20*, 692–695. [CrossRef]
82. Possingham, H.P.; Andelman, S.J.; Noon, B.R.; Trombulak, S.; Pulliam, H.R. *Making Smart Conservation Decisions. Conservation Biology: Research Priorities for the Next Decade*; Soule, M.E., Orians, G.H., Eds.; Island Press: Washington, DC, USA, 2001; pp. 225–244.
83. Wynne, B. Misunderstood misunderstanding: Social identities and public uptake of science. *Public Underst. Sci.* **1992**, *1*, 281–304. [CrossRef]
84. Gregory, J.; Miller, S. *Science in Public: Communication, Culture, and Credibility*; Plenum Trade: New York, NY, USA, 1198; pp. x, 294.
85. Rejeski, D. GIS and Risk: A Three-Culture Problem. In *Environmental Modeling with GIS*; Goodchild, M.F., Steyaert, B.O., Parks, L.T., Eds.; Oxford University Press: New York, NY, USA, 1993; pp. 318–331.

86. Flather, C.H.; Wilson, K.R.; Dean, D.J.; McComb, W.C. Identifying Gaps in Conservation Networks of Indicators and Uncertainty in Geographic-Based Analyses. *Ecol. Appl.* **1997**, *7*, 531–542. [CrossRef]
87. Mowrer, H.T. Propagating uncertainty through spatial estimation processes for old-growth subalpine forests using sequential Gaussian simulation in GIS. *Ecol. Model.* **1997**, *98*, 73–86. [CrossRef]
88. Regan, H.M.; Ben-Haim, Y.; Langford, B.; Wilson, W.G.; Lundberg, P.; Andelman, S.J.; Burgman, M.A. Robust decision-making under severe uncertainty for conservation management. *Ecol. Appl.* **2005**, *15*, 1471–1477. [CrossRef]
89. Gallo, J.A.; Goodchild, M.F. Mapping the uncertainty of conservation planning as a means towards successful implementation. *Soc. Nat. Resour.* **2012**, *25*, 22–36. [CrossRef]
90. Regan, H.; Ensbey, M.; Burgman, M. Conservation Prioritization and Uncertainty in Planning Inputs. In *Spatial Conservation Prioritization: Quantitative Methods and Computational Tools*; Moilanen, A., Wilson, K., Possingham, H., Eds.; Oxford University Press: Oxford, UK, 2009; pp. 145–157.
91. Stocking, S.H.; Holstein, L.W. Constructing and Reconstructing Scientific Ignorance—Ignorance Claims in Science and Journalism. *Knowl. Creat. Diffus. Util.* **1993**, *15*, 86–210.
92. Friedman, S.M.; Dunwoody, S.; Rogers, C.L. *Communicating Uncertainty: Media Coverage of New and Controversial Science*; LEA's communication series; Erlbaum Associates: Mahwah, NJ, USA, 1999; pp. xiv, 277.
93. Kinzig, A. Uncertainty and the scientist. *Ambio* **2003**, *32*, 329. [CrossRef] [PubMed]
94. Earthwise-LK: The Earthwise Framework SDSS for the Little Karoo of South Africa. Available online: https://github.com/EarthwiseFramework/Earthwise-LK (accessed on 1 October 2022).
95. Prototype-IT: The Earthwise Framework SDSS for the Islands Trust of British Columbia, Canada. Available online: https://github.com/EarthwiseFramework/Prototype-IT (accessed on 1 October 2022).
96. Gallo, J.A.; Lombard, A.T.; Cowling, R.M. Conservation Planning for Action: End-User Engagement in the Development and Dual-Centric Weighting of a Spatial Decision Support System. *Land* **2023**, *12*, 1. [CrossRef]
97. UNEP; CBD. First Draft of the Post-2020 Global Biodiversity Framework, United Nations Environment Programme, Convention on Biological Diversity. Open Ended Working Group. 2021. Available online: https://www.cbd.int/doc/c/abb5/591f/2e46096d3f0330b08ce87a45/wg2020-03-03-en.pdf (accessed on 1 October 2022).
98. CNRA. *30 × 30 California: Accelerating Conservatin of California's Nature*; California Natural Resources Agency: Sacramento, CA, USA, 2022. Available online: https://www.californianature.ca.gov/pages/30x30 (accessed on 1 October 2022).
99. Rosa, L.; Belote, T. *Symposium: Conservation Science Principles for Mapping 30 × 30 Objectives and Outcomes*; North American Congress of Conservation Biology: Reno, NV, USA, 2022.
100. MacKinnon, K.; Mrema, E.M.; Richardson, K.; Cooper, D.; Gidda, S.B. Protected and conserved areas: Contributing to more ambitious conservation outcomes post-2020. *Parks Recreat.* **2021**, *27*, 6. [CrossRef]
101. Sheehan, T.; Gough, M. A Platform-Independent Fuzzy Logic Modeling Framework for Environmental Decision Support. *Ecol. Inform.* **2016**, *34*, 92–101. [CrossRef]
102. MPILOT. Available online: https://github.com/consbio/MPilot (accessed on 1 October 2022).
103. Desmet, P.; Cowling, R. Using the species–area relationship to set baseline targets for conservation. *Ecol. Soc.* **2004**, *9*, 11. [CrossRef]
104. Gordon, S.N.; Murphy, P.J.; Gallo, J.A.; Huber, P.; Hollander, A.; Edwards, A.; Jankowski, P. People, Projects, Organizations, and Products: Designing a Knowledge Graph to Support Multi-Stakeholder Environmental Planning and Design. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 823. [CrossRef]
105. Newman, G.; Chandler, M.; Clyde, M.; McGreavy, B.; Haklay, M.; Ballard, H.; Gray, S.; Scarpino, R.; Hauptfeld, R.; Mellor, D.; et al. Leveraging the Power of Place in Citizen Science for Effective Conservation Decision Making. *Biol. Conserv.* **2017**, *208*, 55–64. [CrossRef]
106. Lehtomäki, J.; Moilanen, A. Methods and workflow for spatial conservation prioritization using Zonation. *Environ. Model. Softw.* **2013**, *47*, 128–137. [CrossRef]