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View Point

Integrating ecosystem services modeling and efficiencies in decision-support models conceptualization for watershed management

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ABSTRACT

Decision-making resource stewardship models rely on statistical relationships between management actions and ecosystem services provisioning. The operationalization of management actions benefits from models capable to isolate synergic statistical relationships from trade-offs. We showcase two existing watershed planning studies requiring spatiotemporal operationalization to better schedule management actions. The study in Hawai'i Island (USA) focused on invasive species while another in Babeldaob Island (Republic of Palau) tackled wildfire management. Both planning exercises relied on Ecosystem Management Decision Support to populate hydrologically defined management units for supporting water resource decision-making. In this viewpoint we identify shortcomings and potential future directions aligned with shaping stewardship responses to the interactive constraints of climate mitigation and management costs within a very needed optimization framework capable to operationally support landscape managers and drive solutions on ES management and valuation.

1. Abstract

Resource stewardship decision support tools often rely on statistical modeling of relations between management actions and their effects on ecosystem services provisioning. The ability to operationalize management actions often derives from models that are capable of identifying synergistic and trade-off relationships among services. . We showcase two existing watershed planning studies that would benefit from spatiotemporal operationalization and scheduling of management actions. A first study on Hawai'i Island (USA) focused on invasive species while a second on Babeldaob Island (Republic of Palau) tackled wildfire management. Both planning exercises relied on the Ecosystem Management Decision Support application to populate hydrologically defined management units for water resource decision-making. We identify shortcomings and potential future directions aligned with shaping stewardship responses to the interactive constraints of climate mitigation and factors driving management costs within an optimization framework that could support landscape managers and drive operational solutions on ES management and valuation.

2. Background

Planning for the management of ecosystem services (ES) typically involves weighing trade-offs and identifying synergies. Multi-criteria decision models (MCDM) provide a valuable platform for defining opportunity costs and quantitatively evaluating potential trade-offs and synergies between ES fluxes and the management actions required to protect or enhance their provision (Laurans et al., 2013; Birkhofer et al., 2015). The magnitude of management effects on ES fluxes can be quantitatively embedded into an MCDM by, for example, balancing preferences between ES provisioning and economic productivity. However, traditional cost structures where profits are contingent upon producing commercial products may underestimate the potential to realize alternative revenue streams resulting from ecosystem management. As such, there are relatively few examples in natural resource stewardship where a fully optimized MCDM integrates payments for ES (PES) and drives efficient trade-off evaluation and mitigation.

Optimization methods, such as Pareto frontier optimizations, represent an important evolution in natural resource decision science. Research has shown that optimization enhances decision support efforts by identifying combinations of management actions, including their spatial configuration and timing, that provide the most efficient outcomes for managers (Billionnet, 2013; McKenzie et al., 2014). Methods for incorporating optimization into ecosystem management are mature and readily integrated into existing MCDM solutions. Time is an important element of MCDM solutions because long timelines often compound costs and discount net present value, and long planning horizons can challenge action traceability and continued management support. Similarly, the spatial configuration of MCDM-driven management actions (e.g., spatio-temporal clustering of treatment units) can greatly influence ES and other benefits for a given investment of resources.

Here, we propose that MCDM optimization methods must be integrated into a holistic framing of ES provisioning (e.g., Chee, 2004). Methods such as the Pareto frontier optimizations focus on resource use efficiency (Farley, 2012) and not on increasingly important considerations related to stewardship responsibilities, ecological conditions, legal requirements, or social justice goals (Bennett et al., 2009). However, optimization can incorporate mathematical relationships among various goals too, which can reveal where trade-offs (e.g., progress with respect to one goal decreases while another increases), and synergies (e.g., two goals increase or decrease together) exist among ESs (Bennett

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et al., 2009; Deng et al., 2016). Further, climate change impacts many resource benefits including biodiversity conservation, curbing non-native species invasions, and preventing extensive and severe wildfires (Billionnet, 2013; Reynolds et al., 2014; Keane et al., 2014), which are increasingly being addressed with MCDM applications.

Forward-looking and equitable ES stewardship is enhanced when MCDMs shift their focus from management trade-offs to emphasizing synergies among ES benefits (de Groot et al., 2010; Pascual et al., 2022). This could include assessments of spatial and temporal patterning of modelled ES fluxes associated with management (Marvin et al., 2016). We contend that synergistic MCDMs are underutilized and better suited for balancing resource efficiency considerations with societal mandates designed to mitigate emerging global problems.

Here, we highlight the effectiveness of Pareto optimization to identify strategies that balance competing and synergistic ES goals. We rely on published examples from tropical watershed management (Pascual et al., 2022; Povak et al., 2017, 2020) and show how ecosystem outcomes can be integrated within broader social contexts to achieve holistic decision support. Specifically, we discuss two examples of tropical watershed MCDMs from two different geographies: Hawai'i Island, USA (Povak et al., 2017) and the Republic of Palau (Povak et al., 2020). The Hawaiian study used the Distributed Hydrology-Soil-Vegetation model (DHSVM, Wigmosta et al., 1994) to quantify the impacts of invasive species management on freshwater supply. The Palau study used the same DHSVM model, but in this instance, it used it to highlight restoration and protection-oriented tropical forest management that could increase freshwater supply and reduce ridge to reef sediment deposition. In the present work, the Hawaiian MCDM is refined to integrate Pareto optimization by means of mixed integer programming (MIP) that enables users to quantify ES benefits resulting from optimal scheduling of management actions in space and time (Pascual et al., 2022), paving the way to enhance the Paluan model as well.

3. Marginal benefits for watershed management in Hawai'i island

The central outcome of the Hawai'i Island MCDM (Povak et al., 2017) was the estimation of enhanced freshwater supply through the strategic removal of invasive strawberry guava (SG; *Psidium cattleianum*), while considering conservation value, access limitations, rainfall distribution, and climate change impacts. The MCDM also had the goal of preventing the spread of these invasive trees into uninvaded portions of the study landscape. SG threatens freshwater supplies and native tree populations on the windward side of Hawai'i Island, particularly under climate change, due to its poor water use efficiency when compared to the native trees (Somers and Asner, 2013; Strauch et al., 2017). SG removal was modelled to prioritize management in small watershed catchments that could increase freshwater supply without compromising other resource values and conditions.

Removing SG in a catchment can take days to weeks – depending on the size of the infested area, and its remoteness and infestation level. This study helped managers identify synergies among stewardship outcomes: increased and protected freshwater supply, enhanced biodiversity conservation, and minimized management costs. The selected decision variables in the Hawaiian example did not compromise other ESs as the investment in SG-oriented actions influenced the ecosystem over a limited time. The primary limitation to management was related to accessing high priority catchments in remote areas. Individual catchment treatment consideration was independent of other units – meaning there was no spatial or temporal catchment optimization. In this example, the decision variable for treatment can be represented as,

$$x_{it} = 1 \text{ if catchment } i \text{ is treated to remove invasives in period } t, \ 0 \text{ otherwise},$$

where the assignment of actions across each catchment has no spatial dependencies with other units that might be treated. Determining these spatial and temporal dependencies with Pareto optimizations could increase management possibilities. Accrued costs and management efficiencies derived from treating one unit over another often hinges on a combinatorial search of catchment adjacencies to control the arrangement of treated clusters over space and time.

Temporal and spatial dependencies were added in Pascual et al. (2022) by means of multi-temporal spatial clustering under MIP embedded into Pareto optimization. Schedules from Pascual et al. (2022) integrated spatial and budgetary constraints, and increased freshwater yields up to 20% while assuming a payment of $400 USD per million litres of additional freshwater (Fig. 1 and Fig. 2).

4. Trade-offs in watershed management in the Republic of Palau

The study from Povak et al. (2020) aimed to determine where reforestation of grassland-savanna habitats or tropical forest conservation could reduce sediment impacts on coral reefs. The proposed actions were identified by modelling catchment-level sediment yields under current vegetation conditions compared to converted grassland-savanna cover and fully restored tropical forest cover. Restoration of these conditions requires long-term investment to re-establish native tropical forest while preventing the conversion of forest to grassland-savanna through intentional burning, a common practice on Babeldaob Island. Under the Povak et al. (2020) scenario, improved benefits of ESs from management actions are not immediately realized, rather they are long-term outcomes of restorative actions. This management context contrasts with the Hawaiian study, where ecosystem functioning remained intact except for the forest biomass affected by SG. The decision variable of a similar Pareto frontier optimization for Palau would be:

$$x_{ijt} = 1 \text{ if catchment } i \text{ is managed for treatment } j \text{ in period } t, \ 0 \text{ otherwise},$$

where treatment j imposes the cost of managing ES compared to full savannah or fully forested conditions. The temporal allocation of solution t remains invariant once a catchment i has been scheduled for action, i.e., there is temporal dependence of the decisions along planning periods.

5. Future challenges on ES management and decision-making

The two watershed management case studies compared here highlight the importance of MCDM frameworks that include the role of marginal benefits. The opportunity is clearly shown when invasive species or fire clearing actions are mitigated over short timelines and well-defined locations. Treatment operations require more funding in the short-term than restoration projects scheduled over long periods, especially when considering native species regeneration. However, local communities may be willing to invest in costly but efficient management actions that do not compromise access to ESs over time. The no trade-off context in Hawai'i reduces the gap between management that is focused on following temporally optimized schedules and a synergistic framing that is aligned with more diverse and less restrictive relationships among fluxes of ES, management, and economic production (Hastings et al., 2006; Johnson et al., 2017). Pareto frontier optimization enhanced management scenarios by expanding the range of actions that could be considered by managers while including analytically well-defined bounds (Pascual et al., 2022).

Further, integrating PES and ES valuation into these management scenarios enhances conservation planning for ES fluxes (Paavola and Primmer, 2019), including valuation scenarios framed under PES. The outcomes of SG treatments increase freshwater supply and ecosystem functioning after treatments, which can be monetized to generate revenues for local communities. Synergistic MCDMs can bring a different visualization to interest rate uniformity when valuing a diverse portfolio of ESs (de Groot et al., 2010). For instance, revenues from the extracted

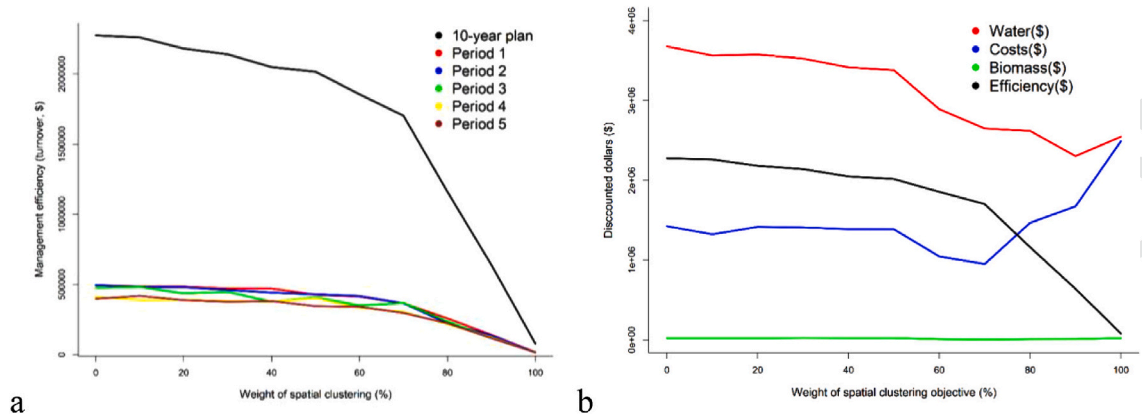

Fig. 1. Pareto Frontiers (PF) presented for the 10-year planning horizon and for every 2-year period when pursuing management efficiency and spatial clustering goals simultaneously (**a** and **b**).

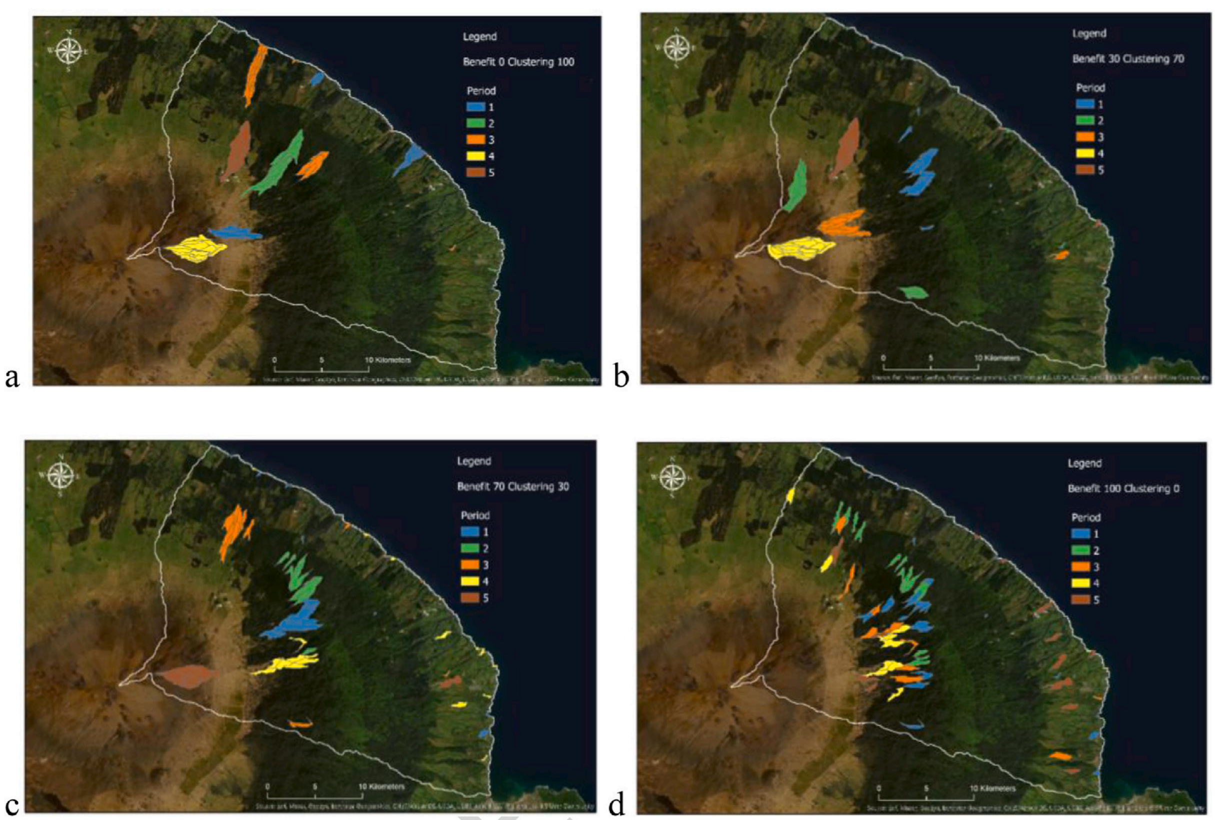

Fig. 2. Pareto Frontiers (PF) decision maps showing the progressive transition from the best solution in terms of spatial and temporal clustering (a; top-left), and when attending only to management efficiency (d; bottom-right). Example presented in Pascual et al. (2022) for the Hawaii island (USA) using data from Povak et al. (2017).

biomass during fuel treatments, or annual carbon payments for protected carbon stocks can vary significantly over time, but valuation still takes place - with a lower or higher interest rate depending on market and resource competition from consumers - over the existing ES (timber resources). In contrast, decision-makers might be tempted to value differently improved ES fluxes that arise with no opportunity costs, and that only emerge after management, such as the freshwater incrementing in Hawai'i. The discounting of revenues from increased freshwater supply can be at a different rate than for the case of scheduled revenues on timber harvesting/biomass removals - subject to more competition from economic actors on forest management.

These considerations of varied MCDM scenarios in ES valuation (i.e., watershed management, sustainable tourism, coral reef protection) can foster more creative and financially beneficial stewardship strategies, especially when managers and modellers are capable of creating a synergistic formulation. The scenario of increasing freshwater availability by means of cost-effective management actions is particularly well-suited and needed in small tropical islands (United Nations Economic Commission for Europe & Food and Agriculture Organization of the United Nations, 2018), where local communities can be involved in stewardship and monitoring of MCDM solutions, thereby requiring reduced financial capital inputs. Re-designing existing management and valuation solutions and creating novel pathways for the spatiotemporal optimization of ESs are two important and timely directions Pareto frontier optimization can support.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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