Contributed Paper

Linking Terrestrial and Marine Conservation Planning and Threats Analysis

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Abstract: *The existence of the Gulf of Mexico dead zone makes it clear that marine ecosystems can be damaged by terrestrial inputs. Marine and terrestrial conservation planning need to be aligned in an explicit fashion to fully represent threats to marine systems. To integrate conservation planning for terrestrial and marine systems, we used a novel threats assessment that included 5 cross-system threats in a site-prioritization exercise for the Pacific Northwest coast ecoregion (U.S.A.). Cross-system threats are actions or features in one ecological realm that have effects on species in another realm. We considered bulkheads and other forms of shoreline hardening threats to terrestrial systems and roads, logging, agriculture, and urban areas threats to marine systems. We used 2 proxies of freshwater influence on marine environments, validated against a mechanistic model and field observations, to propagate land-based threats into marine sites. We evaluated the influence of cross-system threats on conservation priorities by comparing MARXAN outputs for 3 scenarios that identified terrestrial and marine priorities simultaneously: (1) no threats, (2) single-system threats, and (3) single- and cross-system threats. Including cross-system threats changed the threat landscape dramatically. As a result the best plan that included only single-system threats identified 323 sites (161,500 ha) at risk from cross-system threats. Including these threats changed the location of best sites. By comparing the best and sum solutions of the single- and cross-system scenarios, we identified areas ideal for preservation or restoration through integrated management. Our findings lend quantitative support to the call for explicitly integrated decision making and management action in terrestrial and marine ecosystems.*

Keywords: biodiversity, conservation planning, critical transition zone, ecosystem-based management, integrated planning, linked ecosystems, MARXAN, site selection

Concatenación del Análisis de Amenazas y la Planificación de la Conservación Terrestre y Marina

Resumen: *La existencia de la zona muerta en el Golfo de México hace evidente que los ecosistemas marinos pueden ser dañados por insumos terrestres. La planificación de la conservación marina y terrestre requiere ser alineada de manera que represente las amenazas a los sistemas marinos totalmente. Para integrar la planificación de la conservación de los sistemas terrestres y marinos, utilizamos una evaluación de amenazas novedosa que incluyó 5 amenazas trans-sistema en un ejercicio de priorización de sitios para la ecoregión costera Pacífico Noroeste (E.U.A.). Las amenazas trans-sistema son acciones o características en un área ecológica que tienen efectos sobre especies en otra área. Consideramos algunas formas de amenaza de compactación de líneas costeras para sistemas terrestres y amenazas urbanas, agrícolas, silvícolas para sistemas marinos. Evaluamos la influencia de las amenazas trans-sistema sobre las prioridades de conservación mediante la comparación de resultados en MARXAN de 3 escenarios que identificaron prioridades terrestres y marinas simultáneamente: (1) sin amenazas, (2) amenazas en un solo sistema y (3) amenazas en un sistema y trans-sistema. La inclusión de las amenazas trans-sistema cambió el escenario de amenazas dramáticamente. Como resultado, el mejor plan que incluyó amenazas a un solo sistema*

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identificó 323 sitios (161,500 ha) en riesgo por amenazas trans-sistema. La inclusión de estas amenazas cambio la localización de los mejores sitios. Mediante la comparación de las mejores soluciones de los escenarios con amenazas en un sistema y tran-sistema, identificamos áreas ideales para la preservación o restauración por medio de la gestión integral. Nuestros resultados proporcionan soporte cuantitativo al llamado a la toma de decisiones explícitamente integrales y a las acciones de manejo en ecosistemas terrestres y marinos.

Palabras Clave: biodiversidad, ecosistemas conectados, gestión basada en el ecosistema, MARXAN, planificación de la conservación, planificación integral, selección de sitio, zona de transición crítica

Introduction

The majority of the Earth's land surface is linked to oceans by rivers (Boyer et al. 2006) that act as conduits of anthropogenic environmental threats. Through rivers, cross-system threats can affect the viability of terrestrial, coastal, and marine species. These threats include water pollution and habitat loss resulting from land-use change (reviewed in Gray 1997; Boersma & Parrish 1999). Persistent compounds used on the land can damage coral reef systems (Ramade & Roche 2006). Land-based nitrogen loading can alter marine macrophyte community composition (Nielsen 2003) and cause starfish outbreaks that decimate corals (Brodie et al. 2005), toxic phytoplankton blooms (Glibert et al. 2006), or anoxia and fish kills (Rabalais & Turner 2001). Organic carbon released during land conversion can enhance microbial production, switching systems from net carbon sinks to carbon sources (Howarth et al. 1991), possibly altering trophic structure. Even disease propagules can move from land to sea (Harvell et al. 2004).

In addition to river-borne threats, coastal features can threaten biodiversity. Shoreline hardening by structures (e.g., bulkheads) is one of the greatest threats to sandy coasts (Brown & McLachlin 2002), the most common coastal habitat. Coastal structures can also impede sediment accretion in and development of salt marshes or increase erosion rates (Adam 2002). Wave action around these structures can deplete habitat for eelgrass, surf smelt (*Hypomesus pretiosus*), and other species (WSDNR 2000).

Finally, terrestrial species can be threatened by human activities in the ocean. For instance, adult salmon returning to their natal streams provide nutrients to lake and river systems (Schindler et al. 2003), riparian plants (Ben-David et al. 1998), and even bears (Hilderbrand et al. 1999). This nutrient supply has been diminished severely by oceanic fishing, leading to diet shifts in terrestrial species (Hilderbrand et al. 1999) and declines in terrestrial productivity (Gresh et al. 2000).

Cross-system threats are now pervasive in most coastal ecosystems, making their consideration essential for successful management. Fisheries managers may overestimate allowable catch if cross-system threats that constitute a source of mortality are not considered, as is the case in the Gulf of Mexico (Rabalais & Turner 2001). Management plans for endangered species that rely on terrestrial and marine systems—such as Marbled Murrelets (*Brachyramphus marmoratus*)—will fail unless they abate threats in both systems. Conservation planning that ignores cross-system threats may identify places to work or strategies to remove threats that leave protected populations at high risk from external threats (Allison et al. 1998; Boersma & Parrish 1999).

Here we included cross-system threats in a conservation-planning process. We focused on one common planning approach that identified sites that met 3 primary goals: (1) maximal representation of biodiversity, (2) in the minimal amount of area, (3) with the minimal potential for ongoing or future threats (Margules & Pressey 2000; Groves et al. 2002). This approach often involves prioritizing sites across a land- and seascape, but traditional planning efforts and threat assessments treat systems as closed (Stoms et al. 2005), and integration is seldom attempted (but see Ferdaña 2005).

Given the broad use of the term *integration* in conservation planning, we define several terms here. *Concurrent planning* entails separate site-prioritization exercises for terrestrial and marine systems with post hoc integration achieved by compiling analytical results to build a single plan (Vander Schaaf et al. 2006). In *simultaneous planning* the analysis window is set around more than one system so that conservation goals of multiple systems are met in the same analysis and area minimization is achieved in all systems simultaneously. Threats are still only system-specific. This approach has been attempted (Vander Schaaf et al. 2006), but not implemented successfully. The final step toward integration is taken in *integrated planning*, in which the analysis window is set around multiple systems and cross-system threats are included. This approach has never been used, largely because of the difficulty of mapping the zone of influence for cross-system threats.

We used the U.S. Pacific Northwest coast ecoregion (Fig. 1) as a case study to conduct the first integrated conservation-planning exercise. The Nature Conservancy recently used simultaneous planning with single-system threats to complete terrestrial and marine ecoregional

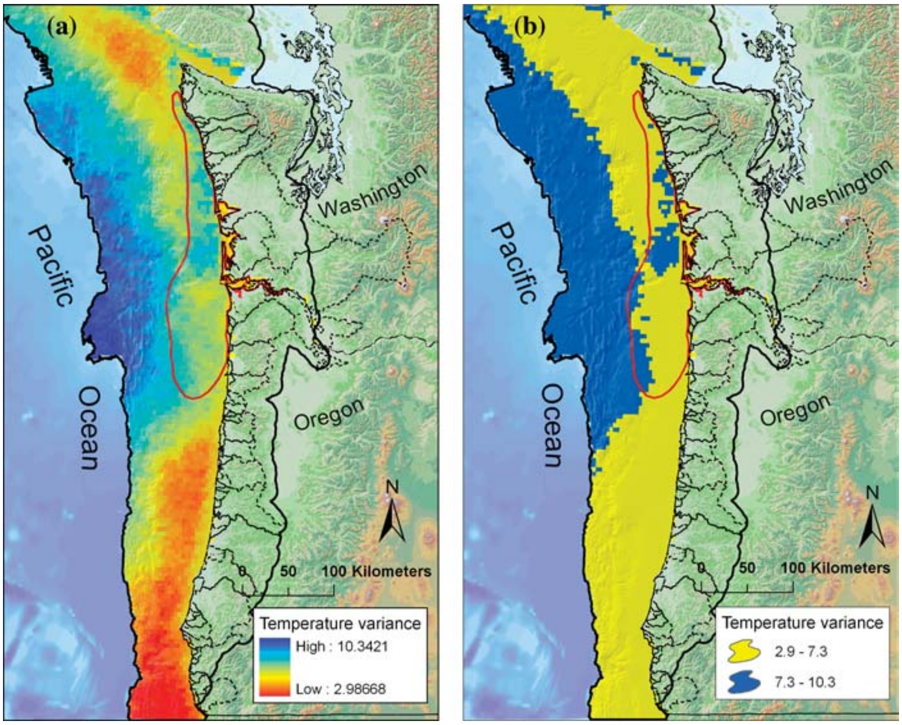

Figure 1. Study area and (a) southern and northern (blue) extents and (b) modeled extent (yellow south of the river and blue north of the river) of the Columbia River plume as indicated by temperature variance of the sea surface. The red line is projected extent of the Columbia River plume created by the CORIE model. The dotted lines on land outline the contributing watersheds used in calculating marine cross-system cost. The solid line outlines the ecoregion, the seaward extent of which is the bottom of the continental shelf break (2500-m isobath).

plans for this area. We used this plan as a reference case and devised a new plan for the same region that included several cross-system threats. The new analysis was a more integrated approach, but was not fully integrated because all major cross-system threats were not included (e.g., ocean fishing as a terrestrial threat). We compared the outputs of a common decision-support tool, MARXAN, for these 2 cases and a base case (no threats) to show the implications of including cross-system threats. The inclusion of these threats lead to the identification of different areas for conservation, increased the total cost of conservation sites, and decreased spatial efficiency. We describe how adding cross-system threats can improve conservation planning that aims to identify the best areas for preservation or threat abatement and restoration.

Methods

We assessed the importance of integrated threats in site selection with 3 different scenarios. We compared their outputs with a decision-support tool, MARXAN (Ball & Possingham 2000; Possingham et al. 2000), a computer software package designed to identify a set of network sites that represent some portion of species or habitats within the bounds of a cost function. MARXAN applications to marine planning exercises have been reviewed elsewhere (Leslie 2005).

In the no-threat scenario all sites were equally suitable for biodiversity because no threats to terrestrial or marine species were included. The single-system threat scenario represented simultaneous terrestrial and marine planning where only system-specific threats are included. This scenario was modeled directly after the exercise used to develop The Nature Conservancy's (TNC) Pacific Northwest Coast ecoregional plan (Vander Schaaf et al. 2006). This plan was recently completed and is a representative case of the current approach to conservation planning TNC uses. Finally, the cross-system threat scenario included both single-system and cross-system threats.

Besides threats, all elements of the 3 scenarios were identical and drawn directly from the approach used for the existing ecoregional plan (Vander Schaaf et al. 2006). The coastal planning units used in that plan, and many others, were not precise and assigned the entire area of any unit straddling the coast both terrestrial and marine information. This approach can overestimate the presence of species, habitats, and threats; thus, planning exercises tend to overrepresent conservation targets. For instance, a 5-km^2 unit that truly contained only 2 km^2 of marine habitat would show 5 km^2 of marine habitat in the traditional approach. Our approach created a 2-km^2 marine unit and a 3-km^2 terrestrial unit.

We considered the same 387 targets (e.g., species, habitats; 55% terrestrial, 45% marine) and the same conservation goals (levels of representation) used in TNC's Pacific Northwest Coast ecoregional assessment (Vander Schaaf et al. 2006). Because our interest was primarily in the effects of cost differences on site selection, we set the boundary length modifier (parameter controlling the minimization of cost vs. perimeter) low to minimize the objective function and overrepresentation of targets.

Table 1. Description of threats considered in single-system and cross-system simultaneous[a] planning scenarios.

Threat	*Data source*[b]	*System affected*[c] *single-system scenario*	*cross-system scenario*
Agricultural area (ha)	NOAA Coastal Change Analysis Program, 2000	T	T, M
Urban area (ha)	NOAA Coastal Change Analysis Program, 2000	T	T, M
Logged area (ha)	NOAA Coastal Change Analysis Program, 2000	T	T, M
Road density (km/km^2)	POCA data, WDFW and Oregon GIS Service Center	T	T, M
Shoreline armoring	ShoreZone data, WDFW; ODFW surveys	M	T, M
Invasive species	PCEIS data, EPA and USGS	M	M
Fishing pressure	OCEAN model, Scholz 2003	M	M

[a] *Conservation-planning approach with more than one ecosystem type inside the analysis window.*

[b] *Key to acronyms and initializations: NOAA, National Oceanic and Atmospheric Administration; POCA, Public land survey, ownership, county and Department of Natural Resources Administrative delineations; WDFW, Washington Department of Fish and Wildlife; ODFW, Oregon Department of Fish and Wildlife; PCEIS, Pacific Coast Estuarine Information System; EPA, Environmental Protection Agency; USGS, United States Geological Survey; OCEAN, Ocean Communities 3E Analysis Network.*

[c] *Key: T, threat to terrestrial species; M, threat to marine species.*

Each scenario was run 100 times in MARXAN (10 million iterations each).

Our 3 planning scenarios differed only in their treatment of threats (Table 1). The no-threat scenario represented hypothetically pristine systems. Following the existing ecoregional plan for the single-system threat scenario, we included agriculture, logging, roads, and urban areas as terrestrial threats and invasive species and shoreline armoring as marine threats (Vander Schaaf et al. 2006). Fishing was added as a marine threat given recently available data on ground-fish harvest. In addition to the set of single-system threats, the threats in the cross-system threat scenario were adjusted by adding shoreline armoring as a terrestrial threat and all terrestrial threats as marine threats (Table 1).

To derive cost, threats were incorporated into MARXAN by combining suitability indices that represent the cumulative threats to each potential site (similar to Davis et al. 1999) with the area of each potential site. Cost is entered into the MARXAN algorithm and minimized in site selection. In the no-threats scenario, the cost of all sites was set equal to 1.

We based the single-system cost for each site on the average level of each threat ($\bar{s}_w$) in the watershed (w for terrestrial threats) containing the site (x) and on the area of the site (A_x). For each potential site, x, with $s = 1, \ldots, S$ threats, the cost was calculated as

$$C_x = A_x + \left(A_x \sum_{s=1}^{S} \frac{\bar{s}_w}{M_s} \right), \tag{1}$$

where M_s is the highest level of threat s in the ecoregion and w is the estuary (invasive species), 9-km^2 block (fishing), or site (shoreline armoring). For example, if the most heavily logged watershed in the ecoregion had 50% logged area on average, then a 500-ha site x in watershed w with 30% average logged area received a logging threat score of 300. If the same site also had an urban threat score of 225, the cost (C_x) would be 1025. Including the area (A_x) of each site in these calculations accounted for different-sized units split along the coast. In this derivation of cost, we assume that all threats were equal and additive and had similarly shaped distribution curves. Nevertheless, this cost score could be dominated by threats with “flatter curves” of uniformly distributed intensity across the ecoregion because normalization to M_s linearly compresses all threats to a scale from 0 to 1, regardless of their absolute values or variations in intensity. Alternative weighting approaches that consider the distribution of the intensity of each threat across the ecoregion or that rank threats on the basis of stakeholder or expert opinion could be used instead.

Cross-system threats and costs were calculated similarly. Shoreline armoring, the only marine cross-system threat, was only applied to terrestrial units directly adjacent to the coast. The single-system threat score for shoreline armoring in the immediately adjacent marine site was added to the single-system terrestrial threat scores. Cost was derived as in Eq. 1.

We assumed that all terrestrial threats were carried conservatively into the ocean by rivers, making them inversely proportional to salinity. We also assumed that all species and habitats respond to all threats in the same way. There are no data describing the actual relationship between salinity, threat level, and response for any of our 387 targets. We observed highly species-specific distributions along the salinity gradient and highly variable behavior of constituents related to different land-based threats. Some contaminants are highly conserved and toxic beyond the realm of river plumes, whereas nutrients cycle quickly and are extremely patchy. Given this variability and the diversity of species and threats we included, we could not justify more complex models.

The equation for marine cost in the cross-system scenario had 3 terms. The first term was the base cost indexed as area (A_x). The second adjusted the base cost for single-system threats and the third adjusted base cost for cross-system threats. For each potential site (x) with $s = 1, \ldots, S$ single-system threats and $c = 1, \ldots, C$ cross-system threats, cost was calculated as

$$C_x = A_x + \left(A_x \sum\nolimits_{s=1}^{S} \frac{\bar{s}}{M_s}\right) + \left(F_{wx} A_x \sum\nolimits_{c=1}^{C} \frac{\bar{c}_w}{M_c}\right), \quad (2)$$

where F_{wx} is the freshwater influence factor (described later) of the most proximal watershed (w) to site x, $\bar{c}_w$ is the average level of cross-system threat c in the coastal watershed (w) most proximal to site x, and M_c is the highest average threat level of cross-system threat c in all watersheds in the ecoregion. A 500-ha marine site (x) with a freshwater influence factor of 0.4 downstream of a watershed with relative threat scores ($\bar{c}_w/M_c$) for logging, urbanization, roads, and agriculture of 0.6, 0.5, 0.8, and 1, respectively, would have a relative cross-system threat score of 580. If the site also had a single-system threat score of 110, the cost would be 1190.

We took a conservative approach for the heavily dammed Columbia River and considered threats in the Columbia basin from only the portion of the watershed below the Bonneville Dam, the farthest downstream dam.

Freshwater Influence Factors

The dams along the Columbia River, the largest river on the west coast of the United States (Whitney et al. 2005), make it difficult to estimate the oceanic plume extent of the river on the basis of discharge. We used long-term variability of sea surface temperature as a proxy for plume extent. River-water temperature is distinct from ocean temperature, and the dynamics of the plume make temperature variance a good proxy for plume extent. The Columbia plume flows south consistently throughout the year, so the southern plume region has low variance in sea surface temperature. Conversely, northern flow of the plume fluctuates dramatically, growing during summer low-wind events (i.e., relaxation events) and winter flows (Hickey et al. 2005).

Thus, we used long-term temperature variation as an index of the influence of the Columbia River plume. We derived 10-year (1995–2004) values of mean annual temperature variance from grids of monthly sea surface temperature (AVHRR Oceans Pathfinder Global 4km Equal-Angle SST Data version 5; Vasquez et al. 1998) (Fig. 1a). We compared our temperature-based proxy with a model-generated, salinity-based extent of the Columbia plume. We used the CORIE model (Baptista et al. 2005) to project the 6-year average annual extent of the surface plume (on the basis of 1996–2005 data) and identified the zone of influence of the Columbia River (all cells with salinity $\leq$31.0 psu). We overlaid the outline of this plume region on a map of our temperature-variance data in ArcGIS 9.1 (ESRI, San Diego, California) (Fig. 1b) and defined the Columbia River influence cutoff as the variance value that corresponded with 31.1 psu. Cells with more stable temperatures generally agreed with the modeled southern plume extent, and cells with more variable temperature generally agreed with the modeled northern plume extent (Fig. 1). Variance values were scored so that cells with the most river influence received a freshwater influence factor of 1.0.

No models exist for projecting the marine extent of other river plumes in the ecoregion, so we used field observations of representative plumes. We mapped the shoreline extent of eight river plumes on the north and west coasts of the Olympic Peninsula, Washington (U.S.A.), during 2004–2005. The range of area in contributing watersheds of these rivers (6–1630 km^2) captured the average size of watersheds in this ecoregion (366 km^2). Sampling by boat is extremely difficult in this region, so we mapped the shoreline extent of plumes by walking in the surf zone with a temperature and salinity probe (model 30M or 58, YSI, Yellow Springs, Ohio) and a global positioning system (etrex Legend, Garmin, Kansas). Each river plume was mapped 2–3 times in the summer (2004) and 2–3 times in winter (2005). All surveys were initiated 1 h after high tide. High river discharge in winter made individual river plumes indistinguishable, so we took a conservative approach and calculated the average summer extent of each plume in ArcView 3.1 (ESRI). We used a linear regression (JMP 5.1, Trolltech, Norway) between watershed area and shoreline extent of the measured plumes ($F_{1,4} = 11.02$, $r^2 = 0.79$; $p < 0.05$) to predict plume extents for all other watersheds. These estimates were used to identify marine planning units under threat from each watershed. Sites intersected by the projected plume extent for a given watershed were given a freshwater influence factor equal to the length of shoreline influenced by the plume. When the projected plumes of two watersheds overlapped, cells in the overlap zone received land-based threats from both watersheds. By only considering the marine planning units immediately adjacent to the coast, we underestimated the offshore influence of larger rivers.

Ecoregional Comparisons

We considered the ability of each scenario to meet several key goals of conservation planning: target and spatial efficiency (i.e., meeting conservation targets in the least space) with minimal threat (low cost). We also asked whether the location of the optimal set of sites chosen by MARXAN was robust across threat scenarios. We used 2 major outputs of MARXAN: (1) the "best solution" (i.e., the single-best set of planning units that most efficiently met our conservation goals in the least amount of area under the least amount of threat) and (2) the "sum solution," which showed the total number of times each site was picked in the best solution over all 100 MARXAN runs for the scenario. The best solution was part of an upper clustering of spatially efficient solutions, so undue emphasis should not be placed on this one solution. Nevertheless, this solution provided a convenient and commonly used means of visualizing one possible good solution. The sum solution gave a more comprehensive view of emergent trends from the larger set of possible configurations that met the conservation goals for a single scenario. Nevertheless, frequently chosen areas should not be taken to represent, by themselves, a complete solution or network, but they can be used to prioritize actions. We referred to the sites included in the best solution as the *best sites* and to those picked frequently in the sum solution as *irreplaceable sites.*

To compare target efficiency, we assessed how well each scenario's best solution met the goal for every species or habitat of interest. For consistency with existing ecoregional planning approaches in this region, we followed the conventions set by Leslie and others (2003) and identified goals as underrepresented ($<$97% of goal), met (98–129% of goal), or overrepresented ($>$130% of goal). In future work examination of the distribution of goal representation could help define less arbitrary category bounds.

To compare spatial efficiency, we assessed whether the total number of sites contained in the best solution varied among scenarios ($n = 100$ MARXAN runs per scenario) across each of the 100 iterations of each MARXAN scenario (analysis of variance [ANOVA], Tukey tests). We used the same approach to assess whether the total cost of all sites included in the best solution varied across threat scenarios. All residuals were normally distributed.

We calculated the Kappa statistic (JMP 5.1, Trolltech, Oslo, Norway) to indicate the amount of similarity in the spatial configuration of the best scenarios not due to chance (Richardson et al. 2006). The Kappa statistic ranges from negative 1 (no overlap) to 1 (complete overlap not due to chance). When overlap between sets of sites is due to chance, the Kappa statistic is 0.

To identify which irreplaceable sites were most threatened by cross-system threats, we mapped the difference between the sum solutions of the single- and cross-system threat scenarios. Large negative scores indicated sites that were chosen highly under the single-system scenario but were avoided in the cross-system threats scenario.

We calculated a robustness score, representing the areas that were selected consistently in the 2 scenarios with threats. Robustness for a site, x, was

$$R_x = \left(\frac{S_x + Cx}{2}\right) - \left(\frac{|S_x - C_x|}{2}\right), \qquad (3)$$

where S_x is the sum solution value for site x in the single-system threat scenario and C_x is the sum solution value for site x in the cross-system threat scenario. The higher the robustness score, the more consistently a site was selected between scenarios.

Results

Overall target efficiency did not change substantially with the addition of single-system or cross-system threats. On average, 45% of targets were met in the no-threat scenario, 50% were overrepresented, and 4.5% were underrepresented. When single- or cross-system threats were added, 47% of all targets were met, 51% were overrepresented, and 2% of targets were not met.

The no-threats scenario had the highest spatial efficiency, selecting the fewest sites in the best solution (Fig. 2a). Spatial efficiency declined significantly when single-system threats were added and again when cross-system threats were included ($F_{2,297} = 23{,}273.5, p < 0.0001$), although the difference between single- and cross-system threat scenarios was relatively small. This efficiency pattern also held for total area in the best solution, with slightly less area in the single-system scenario (2,666,086 ha) than the cross-system scenario (2,669,569 ha).

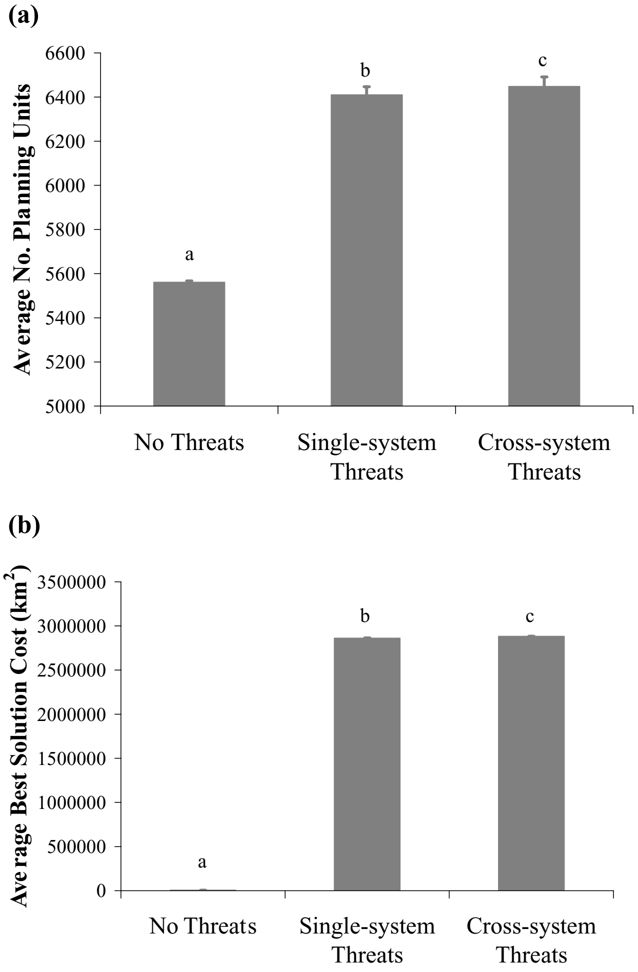

Figure 2. Average (a) number of planning units or sites in and (b) cost of best solutions from planning scenarios. Letters identify significantly different values.

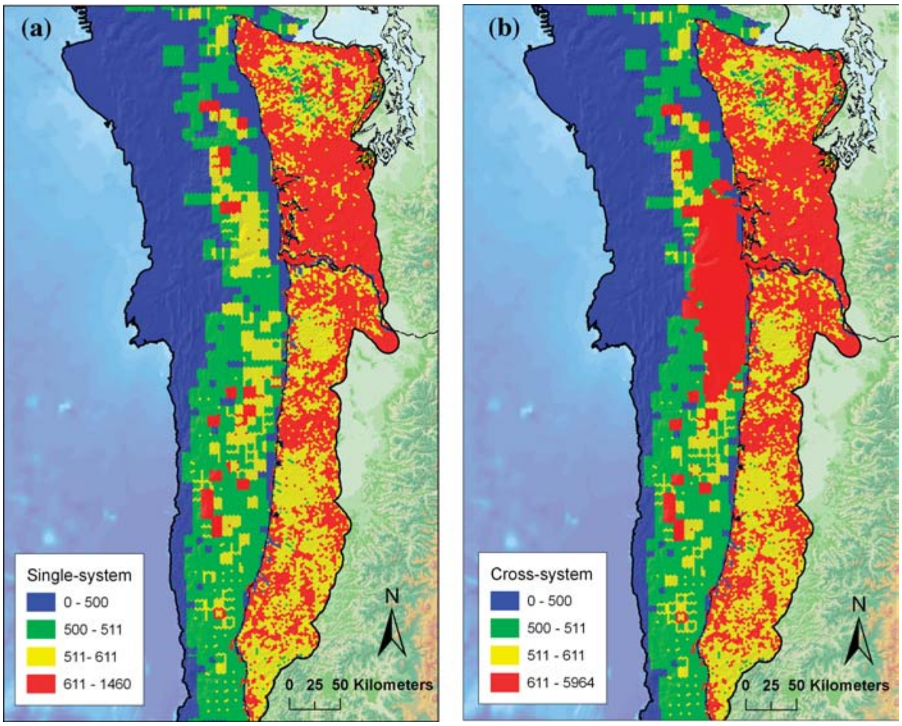

Figure 3. Costs (a function of area and threat levels) of (a) system-specific and (b) cross-system threats in the Pacific Northwest coast ecoregion. Cost scores are a weighted area-based measure calculated as shown in Eq. 1. Included in the cost scores are threats such as fishing in the marine realm and agriculture on land (i.e., single-system threats [a]) and agriculture as a marine threat (i.e., cross-system threats [b]).

Integrating cross-system threats changed the distribution and intensity of cost in space (Fig. 3). The threat posed to the marine realm by the Columbia River resulted in the most obvious cost difference between single-system and cross-system threat scenarios. A large area over the continental shelf concordant with the plume was the highest-cost marine region when cross-system threats were included. Although not visible at the scale of the ecoregion, shoreline costs also differed between single- and cross-system threat scenarios.

The total cost of the best solution also changed among scenarios ($F_{2,297} = 93{,}462{,}915$, $p < 0.00001$). The best solution from the cross-system threat scenario contained sites with the highest total cost (Fig. 2b), and as expected, sites chosen in the no-threat scenario had the lowest cost. The total cost of the cross-system threat's best solution was also significantly higher than the single-system threat's solution, but the relative difference was small (Fig. 2b).

As a result of these changes in the distribution and intensity of costs, there was little similarity in the spatial distribution of best sites (best solution) between the no-threat scenario and the single-system threat scenario (Kappa = 0.14) or the cross-system threat scenario (Kappa = 0.14). There was also very little overlap in space between the locations of best sites in the single-system and cross-system threat scenarios (Kappa = 0.31). Some portion of this spatial shift in selected sites likely reflects within-scenario variation (not tested). Nevertheless, it is visually clear that the cross-system threat scenario avoided choosing units within the Columbia River plume (Fig. 4), where cross-system threats were the most intense. In this region, 323 best sites (161,500 ha) selected by the system-specific threat scenario were not selected as best sites by the cross-system threat scenario. Furthermore, the difference between the sum solutions (outputs that incorporate within-scenario variability) showed that the total area avoided around the Columbia River plume by the cross-system threat scenario was much larger, encompassing 835,500 ha (1,671 units) (Fig. 5a). Areas around the edges of the Columbia plume and along the northern extent of the coast were selected consistently between scenarios (Fig. 5b). These areas were the most robust to changes in threats.

Discussion

We tested the sensitivity of one common conservation-planning approach to the inclusion of threats that cross the land–sea interface. This method, in its commonly used form (with only system-specific threats), chose many sites in the best solution and sum solution that were at risk from external threats. Our approach overcame one of the largest roadblocks to integrated threats assessment because it used relatively simple proxies to represent the influence of river plumes in the ocean (Fig. 1). Conservation planning with cross-system threats avoided at-risk sites (Figs. 4 & 5).

A major advance in conservation planning allowed simultaneous consideration of terrestrial systems, marine systems, and the threats that travel between them. Sea surface temperature variability and field observations of

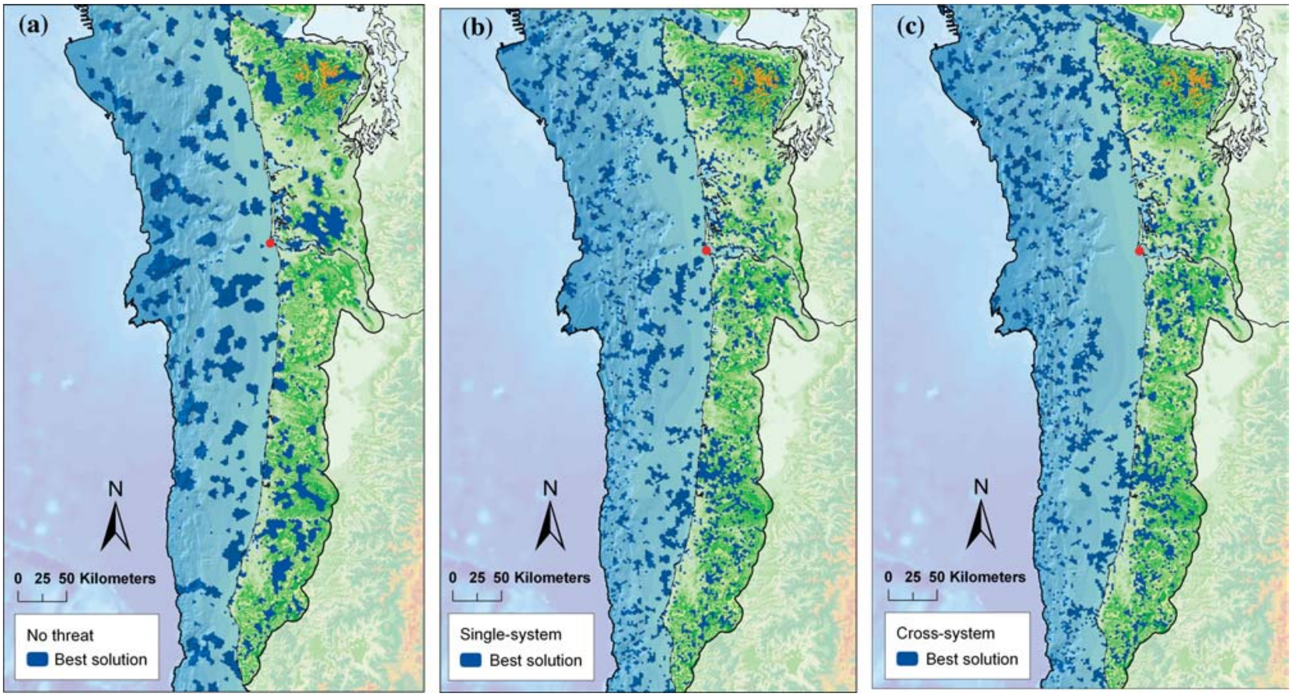

Figure 4. Best solutions from simultaneous MARXAN site-selection scenarios with (a) no threats, (b) single-system threats, and (c) single-system and cross-system threats. Dark blue areas are sites chosen in the best MARXAN solution for each scenario. Many of the best sites chosen near the mouth of the Columbia River (red dot) were not chosen when cross-system threats were included.

shoreline plume extents were used as proxies for the zone of influence of land-based threats in the ocean. Our proxy for freshwater influence of the Columbia River agreed well with a mechanistic model of its plume (Fig. 1). Ideally, one would use a model that incorporates known relationships between environmental factors (e.g., hydrology) and threat-related factors (e.g., roads) to propagate threats into estuaries, which would

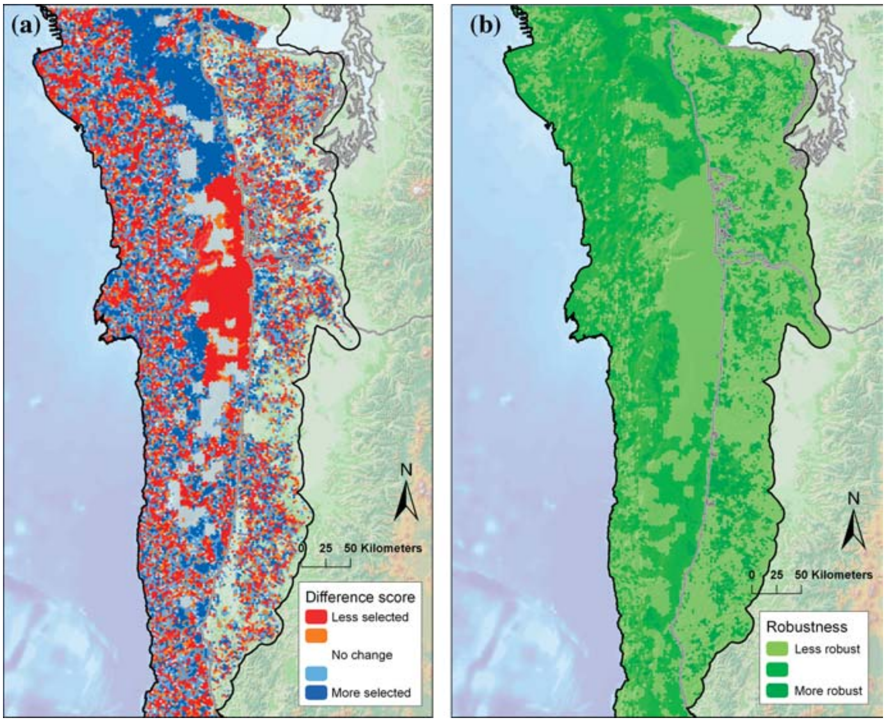

Figure 5. Difference in the MARXAN sum solution when (a) cross-system threats are included and (b) when robustness is included. Blue areas in (a) are those preferred by the scenario with cross-system threats, and red areas are those that were avoided. White areas were chosen equally by both scenarios. A large area (approximately 835,500 ha) off the mouth of the Columbia River was not selected by the scenario with cross-system threats. Dark green sites in (b) were chosen consistently in both scenarios.

link this model to a physical oceanographic model to disperse contaminants into the coastal ocean. This type of model could be combined with known relationships between biota and contaminants to more realistically represent threats.

In most regions development of such an integrated set of models is far from complete. Our results suggest that variance in sea surface temperature can be a useful proxy for freshwater influence anywhere that river and ocean waters have different temperatures and river discharge variability is somewhat understood. With this basic knowledge and the general assumption that contaminants are conservatively mixed into the ocean, cross-system threats could be included in conservation planning at the level presented here with simple analysis of freely available satellite data.

The use of these new methods could be important in identifying the best set of sites to target for conservation action. In the Pacific Northwest Coast Ecoregion the location of sites in the best solution changed dramatically when cross-system threats were included. Only 30% of the best sites identified by the single-system and cross-system threat scenarios were in the same locations (Fig. 3). This result suggests that planning with system-specific threats alone selected many best sites at risk from cross-system threats because explicitly including cross-system threats in planning avoided places that had been identified as conservation priorities (Fig. 4). This was the case both along the shoreline and over the continental shelf.

Comparing the arrangement of sites selected across scenarios can provide useful guidance toward meeting 2 common conservation goals: threat abatement and habitat restoration or preservation. Under the assumptions of our analyses, sites identified as the best sites in the single-system scenario but avoided in the cross-system scenario have high potential for adding to biodiversity representation, but currently suffer from significant cross-system threats. These sites could contribute to biodiversity representation if terrestrial management was aimed at abating cross-system threats. Alternatively, the best sites identified under both single- and cross-system threat scenarios could contribute most to biodiversity representation under current conditions. These sites currently are of high biodiversity value and at low risk from all threats included.

Many of the areas in the plume of the largest river in the ecoregion, the Columbia River, are desirable biodiversity sites under high risk from cross-system threats (Fig. 4). We found that 323 sites (161,500 ha) chosen as best sites with the traditional approach (only system-specific threats) were at risk from threats, such as agriculture, in the Columbia River watershed. Mapping the difference between sum solutions for the single- and cross-system scenarios more clearly represented the full extent of the area at risk from Columbia watershed activities, showing that the conservation value of approximately 835,500 ha of irreplaceable area under single-system threat assessment in the Columbia River plume was diminished by land-based threats (Fig. 5). This situation is not specific to the Pacific Northwest ecoregion and the Columbia River. Globally, 59% of existing marine protected areas (of 1108 assessed) sited based on current planning exercises or ad hoc opportunity, are experiencing a high risk of degradation from coastal development and related activities (Bryant 1995).

The shift in best and irreplaceable sites away from the Columbia River plume area and many sites in other large coastal estuaries in the ecoregion suggests that these areas are currently under too much threat to achieve the goal of protecting representative, diverse marine communities. Nevertheless, the Columbia plume region is highly productive, thanks to the iron and silica delivered by the river (Whitney et al. 2005), making it an important region for fish, including salmonids. Willapa Bay, just north of the Columbia River mouth, produces 10% of the annual U.S. oyster catch (Ruesink et al. 2006). Fisheries and aquaculture managers cannot move these industries to areas under lower threat. Instead, threats must be abated for management to be successful, and our analyses show that this will require action in upstream watersheds. In fact, our analyses explicitly illustrate where cross-system threats need to be abated across the ecoregion (red areas, Fig. 5a).

When preservation of pristine areas is the goal of conservation action, it is essential to identify the areas across a region under the least amount of threat. Irreplaceable sites that were robust, or chosen consistently across scenarios, are theoretically outside the realm of impact of all threats considered. Areas over the northern reaches of the continental shelf and the southwestern edge of the Columbia plume region were robust to additional threats and could provide high conservation value through protection with little additional management (Fig. 5b).

In addition to the spatial orientation of sites, we also assessed cost, spatial efficiency, and target efficiency at the ecoregional scale. All 3 of our scenarios had similar target efficiency. Nevertheless, adding cross-system threats increased overall cost in the best solution and decreased spatial efficiency. Although adding a more realistic set of threats did not improve these aspects of the planning process, these outcomes are more representative of the actual challenges of addressing threats and acquiring sufficient habitat in a highly threatened area like the coastal zone.

We conducted the first simultaneous conservation-planning exercise with cross-system threats for terrestrial and marine systems with a novel planning unit that precisely represents environmental data at the land–sea margin. Our results showed that ignoring threats that travel between terrestrial and marine systems in conservation planning exercises leads to the identification of conservation areas that likely are at substantial risk. These threats can be included in conservation planning by using freely available data and a relatively simple approach. Including cross-system threats changed the outcomes of conservation planning in the U.S. portion of the Pacific Northwest Coast ecoregion. It is yet to be seen whether terrestrial reserves, marine protected areas, or other conservation strategies established after consideration of cross-system threats actually create conditions in which species are more likely to persist. Regardless, our findings lend further support to the call for coordinated decision making and management action in terrestrial and marine systems.

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