Seascape ecology: Identifying research priorities for an emerging ocean sustainability science

Text S1. Invitational letters.

Project outline and instructions for academic scientist respondents
We would like to invite you to contribute to a forward-looking manuscript to help define the priority questions in the application of seascape ecology to support marine conservation and management in the next 10 years.

We believe that your expert knowledge and insight into potential applications of a seascape ecology approach will be valuable in helping to guide the future research agenda for the emerging science of seascape ecology.

We define seascape ecology as the application of concepts, tools and techniques typically associated with landscape ecology to the study of geometric patterns, patterning, and pattern-process relationships in the marine environment. Many of the key themes of seascape ecology are covered in the book *Seascape Ecology* and include ecological connectivity, mapping, modelling and measuring spatial patterns, patch dynamics, holistic network approaches, human use patterns and seascape economics.

The questions we define here are intended to help guide applied research priorities in seascape ecology
over the next 10 years by identifying and justifying questions that, if answered, would
greatly increase the ability to make effective conservation and management actions.

For management actions we mean practices where knowledge of spatial patterns and processes are crucial. For instance, ecosystem-based management, marine spatial planning, MPA design and network design, fisheries management, habitat restoration and creation, impact assessments and monitoring, watershed interventions to manage land-sea interactions, conservation prioritization, etc. Arguably for all decisions where connectivity and spatial context influence outcomes.
There are **four** stages to your participation as a co-author:

Stage 1: Submit initial questions (max. 5) with short written justification (focus on the application) for each question (50-100 words for each question).
Stage 2: Pick your top questions from complete list of all priority questions (comments are optional).
Stage 3: Contribute to text around *priority* questions/themes
Stage 4: Review and comment on draft manuscript and revisions if necessary.

Contribution at ALL stages is required for co-authorship.

Participants are encouraged to take the following into account while thinking of questions:
1. Questions must be of broad geographical relevance but can be focused at any scale with the condition that the question relates to a measurable patterning or pattern-process relationship.
2. The current knowledge gap must be impeding a wider understanding of the importance of spatial patterns and the ecological consequences and management/conservation progress.
Where possible please include a real-world case to explain the relevance of addressing a priority question.
3. Questions must be answerable through a realistic research design that can be completed within the next 10 years. Feel free to horizon scan for instance where technological progress can be foreseen.
4. Questions should NOT be answerable by a simple Yes or No.
5. Answers should be factual, i.e. not based on a value judgment, and should be associated with a measurable outcome.

Project outline and instructions for practitioner invitees

Dear marine/coastal management practitioner/policy-maker,

Last year, we asked the academic community of seascape ecologists to put forward important research questions that if addressed within a 5-10-year period will support the application of seascape ecology to management. They will now be ranking those questions independently using an online survey to create a shortlist.

As leading practitioners of marine management/conservation & policy (including researchers directly assisting practice/policy), we offer you the opportunity to select the research questions that YOU think are important for addressing YOUR information needs over the next 10 years. This will allow us to assess alignment between research priorities perceived by academic scientists and of practitioners. More importantly, this is an opportunity to help shape the research agenda for seascape ecology and other disciplines for better science-to-practice impact. The results will be published in a peer-reviewed journal.

The research questions are grouped under nine themes including the following: seascape change; seascape connectivity; seascape goods and services; seascape mapping, modelling & sampling design; pelagic seascapes, emerging technologies & metrics; restorative and sustainability science; ecosystem-based management; and spatial and temporal scales.

Please Start the Online Survey 'Priority Questions in Seascape Ecology' here

It should only take 15-20 minutes and has been designed to be time-efficient. If you do not feel able to evaluate the questions, then please feel free to send to a colleague. At the end of the survey we ask for your name, but all responses will be treated and analysed anonymously.

If you find any gaps in the research questions across these themes that both fit the scope of seascape ecology and would make a significant contribution to your decision making, then please do send us your additional research questions so that we can include them for all to see.

We thank you for your time.

Best wishes
Simon, Katherine & Phil

Table S1. All 55 research questions that entered the online questionnaire in Step 2 of the prioritisation process. The number in brackets after each question is the proportion (%) of all academic scientist and practitioner respondents that selected the question as important for advancing applied research. Within each of nine research themes the questions are listed in order (highest to lowest) of perceived importance using the proportion (%) of all academic scientists selecting each question and the practitioner vote alongside for comparison.

Academics' vote (%)	Practitioners' vote (%)	Research themes & questions
		1. Seascape change
71	65	Q3. What are the consequences of climate change (*i.e.*, sea-level rise, changes to oceanographic conditions and primary productivity) on seascape structure and function?
69	68	Q27. How can seascape ecology enhance our understanding of, and predictive performance of, species and community responses to changing seascape configuration (*e.g.*, pattern of loss, gain, fragmentation)?
60	36	Q42. How will multiple global change stressors potentially affect seascape connectivity (e.g. migratory marine vertebrates)?
60	77	Q8. How can seascape ecology contribute to understanding the impacts of processes such as fragmentation and habitat loss on resilience and the identification of spatial pattern-dependent tipping points?
60	81	Q13. How can seascape ecology help set ecologically meaningful goals and targets for management in a changing ocean?
57	74	Q36. How can seascape ecology inform ecological risk assessments of anthropogenic impacts (e.g. climate change)?
57	65	Q46. How will climate change and other anthropogenic impacts influence how landscape conditions impact on coastal seascapes?
57	52	Q22. How do range extensions or contractions of habitat-forming species alter seascapes and their function?
51	84	Q35. How can seascape ecology be used to better understand anthropogenic impacts (including cumulative impacts and synergistic effects) in the sea and at the land-sea interface?
49	45	Q39. How can seascape ecology help predict the organismal traits that will result in species persistence under climate change?
49	39	Q43. How does the composition and spatial arrangement of seascapes influence carbon sequestration?

2. Seascape connectivity		
80	81	Q15. How can seascape ecology be used to prioritise efforts to manage (enhance; maintain; mitigate) connectivity?
80	48	Q14. How do different seascapes contribute to patterns of dispersal for species expanding their range (*e.g.*, invasive species, re-locations, climate shifting, recovering populations)?
77	74	Q4. In which seascapes and over which scales do connectivity effects most improve the impact of management actions and what connections are most critical for ecosystem function, biodiversity, and ecosystem services (*e.g.*, provisioning, regulating, supporting)?
71	71	Q12. How does connectivity modify the resistance to disturbance and recovery of ecological entities (from populations to ecosystems)?
63	52	Q17. Where do species of conservation concern aggregate, what corridors exist among areas of high use, and are these influenced by the presence or absence of conservation measures over time?
51	65	Q52. How do spatial and temporal patterns in coastal land use influence seascape structure and function?
49	45	Q32. How can seascape genetics be used to inform management decisions?
34	29	Q33. How should we integrate information on large-distance interconnected conditions (e.g. ecoclimatic teleconnections, into strategic planning in marine management?
26	29	Q47. How can seascape ecology help to identify, prioritise, and enhance urban blue spaces for health and well-being?
23	42	Q55. How can seascape ecology help understand the influence of a focal patch on the surroundings and the surroundings influence on a focal patch?
3. Restoration & sustainability science		
80	68	Q5. How can seascape ecology inform the design and assessment of seascape restoration and creation efforts to improve success?
63	58	Q37. How can seascape ecology inform the design and assessment of artificial structures and built coastal habitats?
43	66	Q29. How can we best integrate a holistic systems approach into seascape ecology to serve as a sustainability science for the ocean?
37	48	Q40. How do seascape patterns and processes influence human dimensions (i.e. values, perception, culture)?

		4. Ecosystem-based management
91	**84**	Q1. How can seascape ecology be applied to inform conservation prioritisation and the design of spatial management strategies (e.g. marine protected areas [MPA] networks, dynamic MPAs, land-sea corridors, spatial action mapping, spatial planning)?
74	**71**	Q16. How can seascape connectivity be integrated into marine spatial planning?
71	**65**	Q23. What attributes of seascape patterns can be used to provide metrics or indicators to determine ecosystem health?
71	**52**	Q20. How can seascape ecology contribute to fisheries management by considering spatial variability in pelagic seascapes?
69	**45**	Q31. How can seascape ecology enhance ecosystem-based management in the open oceans?
66	**84**	Q28. How can seascape ecology be applied to support the monitoring and assessment of management actions to evaluate their effectiveness?
57	**77**	Q38. How do the effects of seascape context and connectivity modify conservation outcomes, and over what scales for which species and ecosystems?
40	**65**	Q41. What are the needs of coastal managers to increase their capacity to utilise a seascape approach?
37	**29**	Q50. How do alternate stable states in local patches influence the viability of metapopulation networks, and how can local management efforts be maximised to scale to metapopulations?
14	**32**	Q54. What would the holistic terrestrial concept of working landscapes look like as a marine-based working seascapes implementation?
		5. Seascape mapping, modelling & sampling design
74	**77**	Q10. How can seascape ecology be used to improve ecological modelling for predicting the geographical distribution of biota?
66	**74**	Q48. How much structural detail do we need to include when making habitat maps to detect and explain ecologically meaningful spatial patterns?
66	**55**	Q49. How can seascape sampling designs for surveys and monitoring be optimised through consideration of differing structural patterns to reduce bias?
60	**61**	Q26. How can seascape ecology be used to inform experimental approaches (*e.g.*, impact assessment); and how can experimental approaches be used in seascape ecology?
51	**52**	Q33. How can we best measure and map spatial and temporal errors and data caveats associated with seascape mapping and analyses to improve communication of uncertainty?

51	**42**	Q44. How should seascape ecology provide measures of evidence on ecological relationships that avoid the limitations of conventional statistical significance testing (*i.e. p*-values)?
49	**42**	Q34. In what context should seascape patterns be represented as continuously varying (gradients) data versus internally uniform patches (patch-mosaics) and what are the consequences?
40	**42**	Q25. How do we name and classify seascape types to develop a global seascape classification scheme?
	6. Spatial and temporal scale	
94	**77**	Q2. How should seascape ecology identify the relevant spatial and temporal scales over which patterns and processes are linked to inform management practices?
69	**71**	Q11. How can the multi-scaled approach often applied in seascape ecology assist in scaling solution-oriented marine management approaches relevant to local, state, national and international levels of coastal management and policy?
57	**61**	Q19. What are the appropriate spatial and temporal scales for assessments of seascape resilience?
	7. Seascape goods and services	
63	**58**	Q9. Which seascape types provide maximum benefits in terms of biodiversity, productivity, support optimal functional connectivity and how will these functions change through re-structuring processes resulting in habitat loss and fragmentation?
57	**42**	Q21. How do seascape patterns influence the flow and quality of ecosystem goods and the estimation of value and risk in natural capital assessments?
54	**77**	Q45. What methods are most effective for linking spatial characteristics of the seascape to social, cultural and ecosystem service values that are meaningful to management practitioners and communities?
	8. Pelagic seascapes	
72	**74**	Q20. What combination of survey and analytical techniques are most appropriate for characterising pelagic seascapes?
40	**39**	Q53. Are benthic seascape patterns reliable predictors of pelagic seascape patterns and vice versa?
	9. Emerging technologies and metrics	
86	**87**	Q6. What are the most useful metrics and indicators for characterising and monitoring spatio-temporal patterns in seascapes and over what scales should these be measured?

74	74	Q7. How can seascape metrics be applied to help link spatial patterns to ecosystem function (*e.g.*, understanding and modelling the responses of mobile animals to physical conditions)?	
54	81	Q24. How can we use emerging sensor technologies and data integration techniques to improve seascape mapping?	
46	58	Q30. How can we best apply AI to enhance seascape ecology?	

Table S2. Ranked priority research questions based on academic scientists and practitioners selecting their top 10 subset of most important questions (Step 3) from those questions initially selected as important by them in Step 2. The rank is numbered from 1 (most selected top 10 question) to 16 (least selected question) for the application of seascape ecology to marine management. The questions are listed in order (highest to lowest) of perceived importance based on the academic scientist respondents to allow easy cross-comparison with practitioner priorities. QID = Question unique identifier in order of academics' rank. The proportion of votes received was used to classify questions into upper (≥24% [blue]), middle (11-23% [grey]) and lower (>11% [light blue]) terciles with the upper tercile class being the highest priority tier of research questions.

QID	Seascape ecology research questions	Academics' rank & vote (%)	Practitioners' rank & vote (%)
1	How can seascape ecology be applied to inform conservation prioritisation and the design of spatial management strategies (e.g. marine protected area [MPA] networks, dynamic MPAs, land-sea corridors, spatial action mapping, spatial planning)?	1 (51)	3 (39)
2	How should seascape ecology identify the relevant spatial and temporal scales over which patterns and processes are linked to inform management practices?	2 (46)	5 (32)
3	What are the consequences of climate change (i.e. sea-level rise, changes to oceanographic conditions and primary productivity) on seascape structure and function?	3 (43)	10 (16)
4	In which seascapes and over which scales do connectivity effects most improve the impact of management actions and what connections are most critical for ecosystem function, biodiversity, and ecosystem services (provisioning, regulating, supporting)?	4 (40)	6 (29)
5	How can seascape ecology inform the design and assessment of seascape restoration and creation efforts to improve success?	4 (40)	3 (39)
6	What are the most useful metrics and indicators for characterising and monitoring spatio-temporal patterns in seascapes and over what scales should these be measured?	5 (37)	1 (52)

7	How can seascape metrics be applied to help link spatial patterns to ecosystem function (e.g. understanding and modelling the responses of mobile animals to physical conditions)?	6 (34)	11 (13)
8	How can seascape ecology contribute to understanding the impacts of processes such as fragmentation and habitat loss on resilience and the identification of spatial pattern-dependent tipping points?	7 (29)	9 (19)
9	Which seascape types provide maximum benefits in terms of biodiversity, productivity, support optimal functional connectivity and how will these functions change through re-structuring processes resulting in habitat loss and fragmentation?	7 (29)	6 (29)
10	How can seascape ecology be used to improve ecological modelling for predicting the geographical distribution of biota?	7 (29)	9 (19)
11	How can the multi-scaled approach often applied in seascape ecology assist in scaling solution-oriented marine management approaches relevant to local, state, national and international levels of coastal management and policy?	7 (29)	8 (23)
12	How does connectivity modify the resistance to disturbance and recovery of ecological entities (from populations to ecosystems)?	7 (29)	12 (10)
13	How can seascape ecology help set ecologically meaningful goals and targets for management in a changing ocean?	8 (26)	6 (29)
14	How do different seascapes contribute to patterns of dispersal for species expanding their range (e.g. invasive, re-locations, climate shifting, recovering populations)?	8 (26)	12 (10)
15	How can seascape ecology be used to prioritise efforts to manage (enhance; maintain; mitigate) connectivity?	9 (23)	5 (32)
16	How can seascape connectivity be integrated into marine spatial planning?	9 (23)	8 (23)
17	Where do species of conservation concern aggregate, what corridors exist among areas of high use, and are these influenced by the presence or absence of conservation measures over time?	9 (23)	9 (19)
18	How can seascape ecology contribute to fisheries management by considering spatial variability in pelagic seascapes?	9 (23)	12 (10)
19	What are the appropriate spatial and temporal scales for assessments of seascape resilience?	9 (23)	8 (23)

20	What combination of survey and analytical techniques are most appropriate for characterising pelagic seascapes?	10 (20)	10 (16)
21	How do seascape patterns influence the flow and quality of ecosystem goods and the estimation of value and risk in natural capital assessments?	10 (20)	11 (13)
22	How do range extensions or contractions of habitat-forming species alter seascapes and their function?	10 (20)	14 (3)
23	What attributes of seascape patterns can be used to provide metrics or indicators to determine ecosystem health?	11 (17)	6 (29)
24	How can we use emerging sensor technologies and data integration techniques to improve seascape mapping?	11 (17)	4 (35)
25	How do we name and classify seascape types to develop a global seascape classification scheme?	11 (17)	12 (10)
26	How can seascape ecology be used to inform experimental approaches (e.g. impact assessments) and how can experimental approaches be used in seascape ecology?	12 (14)	12 (10)
27	How can seascape ecology enhance our understanding of, and predictive performance of, species' and community responses to changing seascape configuration (e.g. pattern of loss, gain, fragmentation)?	12 (14)	12 (10)
28	How can seascape ecology be applied to support the monitoring and assessment of management actions to evaluate their effectiveness?	12 (14)	2 (42)
29	How can we best integrate a holistic systems approach into seascape ecology to serve as a sustainability science for the ocean?	12 (14)	6 (29)
30	How can we best apply AI to enhance seascape ecology?	12 (14)	12 (10)
31	How can seascape ecology enhance ecosystem-based management in the open oceans?	12 (14)	10 (16)
32	How can seascape genetics be used to inform management decisions?	12 (14)	13 (6)
33	How can we best measure and map spatial and temporal errors and data caveats associated with seascape mapping and analyses to improve communication of uncertainty?	12 (14)	13 (6)
34	In what context should seascape patterns be represented as continuously varying (gradients) data versus internally uniform patches (patch-mosaics) and what are the consequences?	13 (11)	13 (6)

35	How can seascape ecology be used to better understand anthropogenic impacts (including cumulative impacts and synergistic effects) in the sea and at the land-sea interface?	13 (11)	7 (26)
36	How can seascape ecology inform ecological risk assessments of anthropogenic impacts (e.g. climate change)?	13 (11)	8 (23)
37	How can seascape ecology inform the design and assessment of artificial structures and built coastal habitats?	13 (11)	13 (6)
38	How do the effects of seascape context and connectivity modify conservation outcomes, and over what scales for which species and ecosystems?	13 (11)	10 (16)
39	How can seascape ecology help predict the organismal traits that will result in species persistence under climate change?	13 (11)	12 (10)
40	How do seascape patterns and processes influence human dimensions (values, perception, culture)?	14 (9)	11 (13)
41	What are the needs of coastal managers to increase their capacity to use a seascape approach?	14 (9)	9 (19)
42	How will multiple global change stressors potentially affect seascape connectivity (e.g. migratory marine vertebrates)?	14 (9)	12 (6)
43	How does the composition and spatial arrangement of seascapes influence carbon sequestration?	14 (9)	12 (10)
44	How should seascape ecology provide measures of evidence on ecological relationships that avoid the limitations of conventional statistical significance testing (*i.e. p*-values)?	14 (9)	12 (10)
45	What methods are most effective for linking spatial characteristics of the seascape to social, cultural and ecosystem service values that are meaningful to management practitioners and communities?	15 (6)	5 (32)
46	How will climate change and other anthropogenic impacts influencing landscape conditions impact on coastal seascapes?	15 (6)	8 (23)
47	How can seascape ecology help to identify, prioritise, and enhance urban blue spaces for health and well-being?	15 (6)	13 (6)
48	How much structural detail do we need to include when making habitat maps to detect and explain ecologically meaningful spatial patterns?	15 (6)	6 (29)

49	How can seascape sampling designs for surveys and monitoring be optimised through consideration of differing structural patterns to reduce bias?	15 (6)	13 (6)
50	How do alternate stable states in local patches influence the viability of metapopulation networks, and how can local management efforts be maximised to scale to metapopulations?	15 (6)	15 (0)
51	How should we integrate information on large-distance interconnected conditions, e.g. ecoclimatic teleconnections, into strategic planning in marine management?	15 (6)	15 (0)
52	How do spatial and temporal patterns in coastal land use influence seascape structure and function?	16 (3)	11 (13)
53	Are benthic seascape patterns reliable predictors of pelagic seascape patterns and vice versa?	16 (3)	13 (6)
54	What would the holistic terrestrial concept of 'working landscapes' look like as a marine-based 'working seascapes' implementation?	16 (3)	14 (3)
55	How can seascape ecology help understand the influence of a focal patch on the surroundings and the surroundings' influence on a focal patch?	16 (3)	14 (3