Barr Al Hikman

a pristine coastal ecosystem in the Sultanate of Oman

Current state of knowledge and future research challenges

Preface

Coastal ecosystems are among the most productive ecosystems in the world, providing a large number of ecosystem services to human society. Inspired by the UN Sustainable Development Goal 14 (SDG) to "conserve and sustainably use the oceans, seas and marine resources for sustainable development", obtaining fundamental and applied knowledge about the functioning and exploitation of coastal areas has become increasingly urgent.

Barr Al Hikman in the Sultanate of Oman is a relatively pristine coastal area which provides feeding and nursery grounds for a remarkably diverse community of shorebirds, turtles, fishes, crabs, and other benthic invertebrates. Such rich and pristine ecosystems have become rare and as such are, therefore, among the most precious heritage areas of the world. As a consequence, Barr Al Hikman provides unprecedented research opportunities to disentangle complex interacting processes that shape natural coastal ecosystems.

Over the past years, marine ecologists of the NIOZ Royal Netherlands Institute for Sea Research were involved in numerous scientific expeditions to Barr Al Hikman. They were impressed by the scenery of the area, the research potential of the ecosystem and the support of the local scientific community. In this report, they have summarized their observations on the coastal ecology of the area and outline future research challenges.

I would like to thank the people of Oman for their hospitality, and sincerely hope that this report may function as a starting point for further and more structural scientific collaboration.

Prof Dr H. Brinkhuis
Director NIOZ

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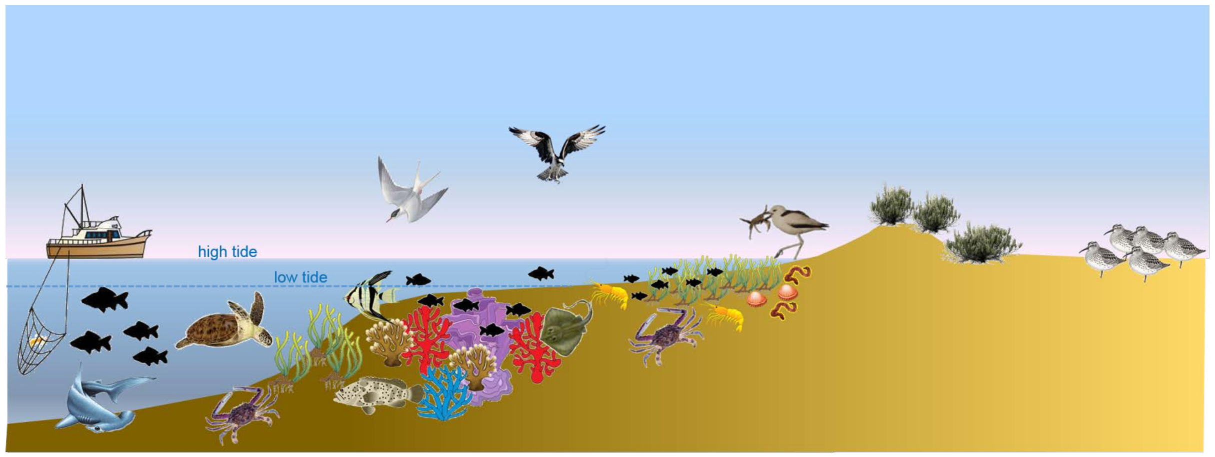
الملخص:

تستقطب منطقة الأراضي الرطبة ببر الحكمان أهمية متزايدة على الصعيد العالمي من منطلق أهميتها واسهامها البيئي الساحلي الفريد من نوعه كمنطقة أراضٍ رطبة غنية بالتنوع الحيوي ومهمة في فهم النظم البيئية الطبيعية. ومنذ عام 2007 اتخذت المنطقة بعدًا آخر حيث أصبحت مزارا سنويا للعديد من العلماء والباحثين من عدة مؤسسات وجامعات بحثية عالمية في مجال علوم البيئة البحرية بما فيها المعهد الملكي الهولندي لأبحاث البحار (نيوز) والذي يقوم بدراسة البيئة البحرية للمنطقة بالتعاون الوثيق مع شركاء وباحثين محللين.

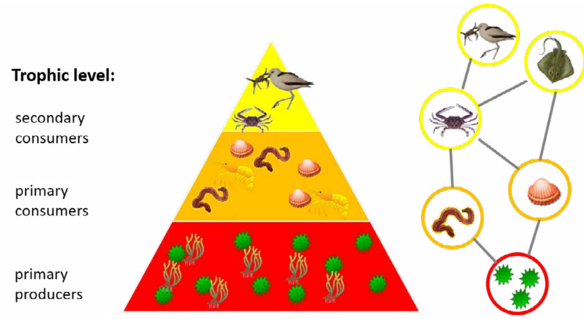
وفي مارس / آذار 2017، زار وفد من قسم النظم البيئية الساحلية بالمعهد الملكي الهولندي منطقة بر الحمان وذلك لاستكشاف آفاق البحث والتعاون في المستقبل في هذا المجال بحكم الخبرات البحثية العديدة في عدة مناطق عالمية شبيهة بمواصفات منطقة المد والجزر ببر الحكمان مثل منطقة المد والجزر ب(بانك ارجوين بموريتانيا) ومنطقة بحر وادن في بحر الشمال، شمال غربي أوروبا. وقد أثارت المنطقة إعجاب الباحثين بسبب التنوع الإحيائي الفريد من نوعه وتوافر جميع ظروف البيئة البكر في منطقة بر الحكمان. وبذلك تقرر ضرورة جمع المزيد من المعلومات والمعارف التي قد تسهم في فهم هذا النظام البيئي بشكل أوسع بما يمهد لمعرفة أكثر تفصيلا وتحديد أدق للثغرات المعرفية الأكثر إلحاحا فيما يتعلق بأداء النظام البيئي البحري بمنطقة بر الحكمان في ظل عالم متسارع التغير من الناحية البيئية. سيسلط هذا التقرير الضوء على الخطوات والتوجهات المستقبلية في دراسة المنطقة بشكل أكثر شمولية.

تقع منطقة بر الحكمان في بحر العرب ما بين محافظتي الوسطى وجنوب الشرقية بسلطنة عمان. وقد تشكلت منطقة بر الحكمان نتيجة تغيرات مختلفة في مستوى سطح البحر عالميا على مر العصور مقرونةً بتغيرات جغرافية محلية في مستوى ارتفاع سطح الأرض. والذي بدوره تسبب في غمر المنطقة بمياه البحر على مدى آلاف السنين الماضية. وفي الوقت الحاضر، يتألف النظام البيئي لبر الحكمان من ثلاثة موائل بيئيةٍ مترابطة: (1) السبخات الساحلية، (2) المسطحات الطينية بمناطق المد والجزر، و (3) مياه البحر العميقة، موضح في (الشكل 1). تغطي السبخات البحرية ما مساحته 1400 كم مربع، ما يعد أكبر تجمعٍ من هذا النوع



الشكل 1: الموائل البيئية الثلاثة المكونة لنظام الأراضي الرطبة ببر الحكمان، من اليسار إلى اليمين: مياه المحيط، مياه بحر عمان، المسطحات الطينية الرسوبية بمنطقة المد والجزر الساحلية، والسبخات الساحلية بشبة الجزيرة.

من السبخات في سلطنة عمان. وتشكل الكثبان الرملية الساحلية، جنبا إلى جنب مع بعض أشجار القرم الصغيرة المتناثرة على الساحل هامشا طوليا ساحليا يتراوح ما بين 5-20 متر تتخلله عرضيا العديد من الاخوار الصغيرة. وتشكل منطقة المد والجزر الرابط بين الخط الساحلي ومياه البحر، والتي تتكون من مسطحات طينية قاحلة نسبيا جنبا الى جنب مع مروج الأعشاب البحرية وبعض أحواض وقنوات المد والجزر.

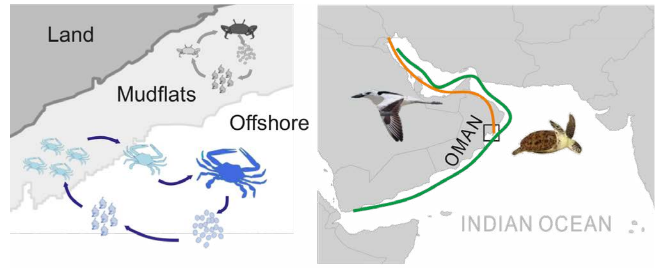


الشكل 2: اليسار: مثال على الهرم الغذائي للبيئات البحرية يظهر فيه الكتلة الحيوية في كل مستوى غذائي (لا يتضمن المستوى الأعلى والذي يحتوي على أسماك القرش والدلافين أو الحيتان). اليمين: مثال تخطيطي مبسط للشبكات الغذائية موضحا فيه بعض الكائنات المتواجدة بمنطقة بر الحكمان.

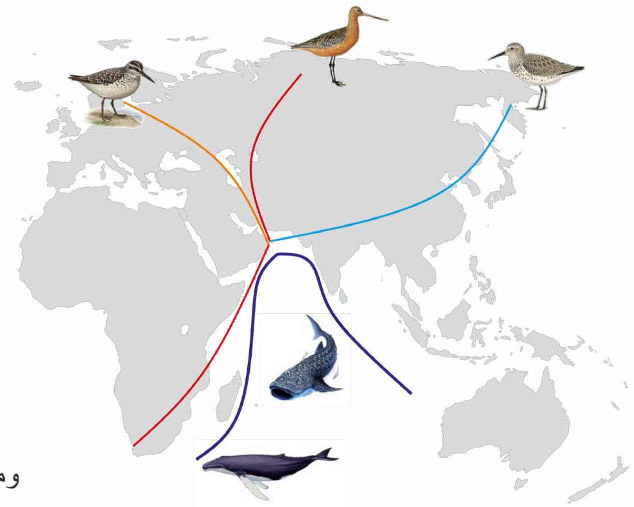
إن الثراء الطبيعي للنظم الساحلية، مثل بر الحكمان وبانك ارجوين وبحر وادن، ينبع من توازن دقيق بين الإشعاعات الشمسية ممثلتا في كمية الحرارة، وبين حركية المياه وكذلك دورة المغذيات البحرية. وبالنسبة لبر الحكمان، يأتي جزء مهم من إمدادات المغذيات من المياه البحرية الباردة العميقة التي تقع بالقرب من الخط الساحلي والتي تنبثق من العمق قادمة من المناطق القطبية، علاوة على الغبار المنبعث بسبب الرياح من شرق أفريقيا في الصيف وحوض نهر دجلة والفرات في فصل الشتاء والتي تكون محملة بالعديد من العناصر الغذائية التي تساهم في تكاثر العوالق البحرية المغذية. هذه المواد الغذائية جنبا إلى جنب مع أشعة الشمس الوافرة تساهم في نمو النباتات مثل الأعشاب البحرية، والطحالب وحيدة الخلية والعوالق البحرية على المياه والرواسب (المنتجات الغذائية الأولية). استنادا إلى بعض المعلومات المتناثرة من المصادر العلمية المنشورة، فإن إجمالي الإنتاجية الأولية للنظم الساحلية بشكل عام (من الطحالب وحيدة الخلية والأعشاب البحرية وأشجار القرم) يزيد عن 165,000 طن من الكربون سنويا. ويشمل هذا الرقم تقديرا لإنتاجية المنطقة الاقتصادية الخاصة للسلطنة ، بالمقارنة مع المناطق الاقتصادية الخاصة الأخرى من بين أكثر النظم الساحلية إنتاجية في العالم.

ويسهم النمو النباتي الخصب في تكوين أساس الشبكات الغذائية الساحلية. فالشبكات الغذائية هي شبكات مكونة من عدة كائنات تتغذى على بعضها البعض، حيث يشكل المنتجون الرئيسيون (أي النباتات) الأساس، يليهم المستهلكون الأوليون والثانويون ثم المستهلكون في اعلى الشبكة الغذائية، ويشكل كلٌ منهم "مستوى غذائي" في شبكة (الشكل 2). تعد الكائنات القاعية في بر الحكمان من المستهلكين الأوليين لأنها تتغذى على المواد النباتية وبدورها تصبح موادًا غذائية متاحة بكثرة للحيوانات المفترسة الأعلى في الهرم الغذائي، مثل السرطانات والأسماك والطيور. وكشفت الدراسات الميدانية التي أجراها المعهد الملكي الهولندي للأبحاث البحرية عن وجود تنوع إحيائي كبير في الكائنات القاعية، مع تحديد ما يقرب من 100 نوع من فصيلة الرخويات، والصدفيات، وسرطانات البحر حتى اللحظة. وتهيمن ثلاثة أنواع من الكائنات الرخوية على البيئة القاعية من حيث الاعداد وهي الحلزونات الرخوية (بايرينلا أرابيكا، سيريثيوم سكابريدوم) والكائن الصدفي (بيليسيورا سيلانيكا)، والتي تشكل معا ما نسبته أكثر من 75 في المائة من الكتلة الحيوية الإجمالية.

تم العثور على ما يقارب ٤٠ نوعا من الأسماك خلال مختلف الزيارات الميدانية البحثية في بر الحكمان خلال العقود الماضية وتم تحديد 32 منها حتى الآن. واستنادا إلى ملاحظاتنا وإحصاءات الصيد، يمكن اعتبار المياه الساحلية الضحلة أرضية حضانة هامة لعدة أنواع من الأسماك. بحيث لا زالت المنطقة تحتفظ بتنوع حيوي بكر نسبيا من أسماك (بما في ذلك أسماك الطباق وأسماك القرش)، وهو ما يبدو متناقضا مع العديد من المناطق الساحلية الأخرى في العالم المعرضة للصيد الجائر. ويستقطب الثراء الحيوي الملحوظ في التنوع السمكي تواجد أعداد كبيرة



الشكل 3: رسم تصويري يظهر العلاقة والأهمية الرئيسية لمنطقة بر الحكمان والمياه المحيطة بها كرابط اساسي في دورة حياة العديد من الكائنات الحية المتواجدة بها مثل سرطانات البحر والأسماك والسلاحف والطيور على مستوى الأصعدة المحلية والإقليمية والدولية.



نسبيا من الطيور الساحلية التي تتغذى على الأسماك ما يمثل 20 نوعا مختلفا على الأقل. وتظهر هذه الطيور التي تتغذى على الأسماك عدة أنماط مختلفة من طرق التغذية. بالإضافة إلى ذلك تم خلال المسوح الشتوية في أعوام 1990 و2008 و2013 و2016 حساب قرابة 500.000 ألف من الطيور الساحلية مثلت 42 نوعا ببر الحكمان. ومن بين هذه الأنواع عدد من الطيور البحرية التي تضاعفت أعدادها ثلاثة أضعاف من حيث الوفرة منذ عام 1990 بنسبة تصل إلى 80%. وتجاوزت 18 نوعا منها تخطت نسبة 1% من مجموع الطيور المهاجرة التي تستخدم مسارات الهجرة لقارة آسيا وشرق القارة الأفريقية، وهو الحد المعين من أجل ادراج الموقع باتفاقية الأراضي الرطبة رامسار. وهذا يشير إلى أن بر الحكمان هو مكان شتوي حيوي للطيور البحرية التي تعتمد على المسطحات الطينية للتغذية خلال المد المنخفض، والتي تستخدم الساحل والسبخات الساحلية للتعشيش والنوم خلال المد العالي. وترتبط الطيور المهاجرة هذه المنطقة بنظم بيئية أخرى تبعد حوالي 10,000 كم (الشكل 3).

ومن المهم بمكان أن يتم ملاحظة أنه على الرغم من أن نظام بر الحكمان البيئي يكن تقسيمه إلى عدد من الموائل البيئية (مثل السبخات الساحلية، المسطحات الطينية، المياه البحرية)، إلا أنه لا ينبغي النظر إلى هذه الموائل في عزلة عن بعضها البعض، حيث أنها مترابطة من خلال تفاعلات وعمليات مختلفة (الشكل 1). فعلى سبيل المثال، تربط الطيور البحرية المسطحات الطينية والسبخات الساحلية على نطاق محلي عن طريق حمل براز الغني بالمغذيات والمواد العضوية من أرض التغذية إلى مواقع التعشيش والنوم، وبذلك تقوم بالربط بين عدة أنظمة بيئية مشابهة على المستوى العالمي من خلال الهجرة الموسمية. وبالإضافة إلى ذلك ومن ناحية أخرى، فقد تبين أن السلاحف البحرية تهاجر لمسافات طويلة جدا، بما في ذلك السلاحف المهاجرة من شاطئ التعشيش الشهير برأس الحد في سلطنة عمان، وهو أحد المعالم السياحية الهامة، ولكن أيضا ترتبط هجرتها مع ممرات هجرة أخرى في المياه الإقليمية في أماكن أخرى من الشرق الأوسط (الشكل 3). ومن الأمثلة الواضحة الأخرى على هذه الروابط المكانية هو نقل البقايا العضوية من الأعشاب البحرية إلى الشعاب المرجانية، من خلال كون مروج الأعشاب البحرية كحاضنات لأسماك الشعاب المرجانية. وكذلك هجرة الطيور التي يحركها المد والجزر بين مروج الأعشاب

البحرية والسبخات. وتوضح هذه الأمثلة أنه من الأهمية بمكان النظر في مختلف الصلات المكانية والقريبة التي تربط بين مختلف النظم والموائل البيئية البحرية من أجل فهم أعمق لهذه النظم المهمة.

ويظهر هذا التقرير بوضوح أن نظام بر الحكمان الغني بالتنوع الحيوي مدعوم بموائل بيئية محلية وشبكات غذائية مترابطة عبر تفاعلات وعمليات متعددة محليا وإقليميا وعالميا (الشكل 3). وعلى الرغم من أن هذا النظام البيئي يصنف حاليا بحالة صحية ممتازة من خلال التنوع الحيوي والثروة الإنتاجية، إلا أن هناك عددا من التهديدات المحتملة للقيم الطبيعية للنظام وتشمل هذه التهديدات في الوقت الراهن ظاهرة المد الأحمر الضار في بحر عمان، وممارسات الصيد الجائر، والصيد غير المشروع وصيد السلاحف والإتجار بأعضائها، وأيضًا الآثار المحتملة من تطور البنى التحتية للمشاريع المقترحة بشبه جزيرة بر الحكمان مثل مشاريع الاستزراع السمكي وعمليات التنقيب عن النفط في عرض البحر. وتظهر المعلومات المقدمة في هذا التقرير أن العلوم والأبحاث المتوافرة لم تخدش السطح إلا فيما يتعلق بمعرفة العلاقات الحيوية بين بعض الكائنات. وتعد هذه المعلومات مطلوبة بشدة من أجل تطوير حلول إدارية مستدامة لبر الحكمان في مواجهة تحديات تغير المناخ والأنشطة الاقتصادية المصاحبة.

النتائج والأسئلة البحثية:

إن ادراج العديد من اسئلة البحث التي يجب معالجتها والنظر اليها لتطوير نهج الإدارة المستدامة تشمل تحديد كمية ونوعية واتصال الموائل البيئية المختلفة لنظام بر الحكمان الساحلي والسبخات المحيطة به ومياه البحر.

وتتطلب الإجابة على هذه الأسئلة البحثية، الجمع ما بين مختلف تقنيات أخذ العينات، بما في ذلك أنظمة الاستشعار عن بعد وصور الأقمار الصناعية (على سبيل المثال عن طريق التصوير بالأقمار الصناعية والطائرات بدون طيار) وتتبع بعض الكائنات الحية اثناء تنقلها (مثل الرخويات وسرطانات البحر) والأسماك والسلاحف والطيور. وينبغي أن تكون هذه التتبعات والمراقبة على نطاق مكانى وزمانى وبدقة تسمح باستخلاص المعلومات والأنماط ذات الصلة بتفاصيل كافية للكشف عن الاختلافات المكانية والزمانية لبعض الموائل البيئية (مثل الأخوار الصغيرة) وكذلك اتجاهات حركة مياه الاخوار مع مرور الوقت مع ربطها ببعض الأحداث النادرة (مثل مستوى مياه البحر أثناء حدوث أمواج عاتية). يتطلب الكشف عن العلاقات ما بين الكائنات البحرية (مثل العلاقات بين المفترسات وفرائسها) وبين هذه الكائنات الحية وبيئتها (مثل الآثار التي قد تترتب نتيجة للأمواج العاتية على مروج الأعشاب البحرية) إجراء دراسات ميدانية وتجارب دقيقة تستهدف الإجابة على هذه التساؤلات. ومن خلال اخذ بعض العينات من الرواسب الطينية بما تحتويه من كائنات حية يتم بناء سلاسل غذائية عن طريق استخدام النظائر المستقرة للكربون والنيتروجين في انسجتها لفهم العلاقات الغذائية بينها، كما يساعد هذا في تقييم علاقة التغييرات في المد والجزر وكذلك تناوب الليل والنهار بالحمية الغذائية لبعض أنواع الطيور التي تتغذى على الأسماك وتعتمد في هذا على الظروف البيئية المحيطة. وقد أثبتت بعض التجارب الصغيرة والمحدودة (على سبيل المثال، تجربة وضع بعض الحلزونات العاشبة في ظروف مغمورة بالمياه وظروف أخرى بدون الماء من أجل دراسة ردة فعلها لهذه التغيرات) أنها قد تكون مجدية ومثمرة في فهم بعض طرق التأقلم.

وبشكل عام، فإن المعرفة والمعلومات المتوافرة حاليا في هذا التقرير تشير إلى أن منطقة بر الحكمان تحتوي على نظام بيئي ساحلي بكرٍ نسبيا ويتسم بأهمية وقيمة دولية فيما يتعلق بقيم الحفاظ على الطبيعة كما يتسم بأهمية اقليمية فيما يتعلق بالموارد الطبيعية التي قد يتيحها للاقتصاد. ومن خلال ما تنفرد به هذه المنطقة من تنوع حيوي غني وعلاقات غذائية قوية بين الكائنات الحية المتواجدة فيها فإنها تعد مقصدا ومثالا قد يتيح فهم المواصفات القياسية والطبيعية في وظيفة الأنظمة البيئية المشابهة ومن أجل مقارنة النظم البيئية المتأثرة من جراء الأنشطة البشرية بها. ويسعى المعهد الملكي الهولندي (نيوز) في أن يساهم في فهم علمي ومعرفي أكثر تعمقا في المنطقة من أجل بناء قاعدة بيانات قوية لدعم الإدارة المستدامة في هذا المجال، وبالاشتراك مع نظرائه المحليين من المؤسسات البحثية و الإدارية في هذا المجال.

– Executive summary

The Barr Al Hikman coastal area is increasingly recognized as a globally important wetland area for biodiversity and ecosystem functioning. Since 2007, the area is regularly visited by various consortia including marine ecologists from the Royal Netherlands Institute for Sea Research (NIOZ) to study ecology in close collaboration with local partners.

In March 2017, a delegation of the department of Coastal Systems visited the area to explore outlooks on future research and collaboration. Working also in other coastal intertidal systems in the world, including Banc d'Arguin (Mauritania) and the Wadden Sea (north-western Europe), they acknowledged the unique high biodiversity and its pristine conditions of the Barr Al Hikman area. It was then decided to jointly compile a multidisciplinary literature and observation-based knowledge overview to identifying the most urgent knowledge gaps with regards to the functioning of the Barr Al Hikman system in a changing world. This synopsis and future prospects have been laid down in this report.

Barr Al Hikman area is wedged between the Arabian Sea, the Al Wusta and Ash Sharqiyah region of the Sultanate of Oman. Barr Al Hikman formed as a result of various changes in the global sea level combined with local vertical elevation changes in the Earth's surface, causing episodic marine inundations over the course of the last millennia. At present, the Barr Al Hikman ecosystem consists of three interconnected habitats: (1) coastal sabkhas, (2) intertidal mudflats, and (3) offshore waters (Fig 1). The sabkhas cover an area of 1400 km^2, the largest aggregation of this landscape type in Oman. The coastal dunes, along with scattered small mangrove stands, form a narrow 5-20m fringe between the sabkhas and the intertidal mudflats, and are intersected by several small creeks. The intertidal forms the link between the coastline and the offshore waters and is typified by bare mudflats seagrass meadows, intertidal pools and tidal channels.

The natural richness of coastal systems, such as the Barr Al Hikman, the Banc d'Arguin and the Wadden Sea, originates from a subtle balance between insolation, hydrodynamics and nutrient cycling. For Barr Al Hikman, an important part of the nutrient supply comes from deeper offshore waters that surface near the coastline ('upwelling'), and dust blown in by winds from eastern Africa in summer and the Tigris-Euphrates river basin in winter. These nutrients combined with ample sunlight fuel the growth of plants such as seagrasses, and water-suspended and sediment-based unicellular algae (primary production). Based upon scattered information from literature, the total primary productivity of the coastal system (including unicellular algae, seagrasses and mangroves) adds up to more than 165.000 tonnes carbon per year. This figure includes an estimate of the productivity of Exclusive Economic Zone of Oman (EEZ), which compared to other EEZs ranks amongst the most productive coastal systems of the world.

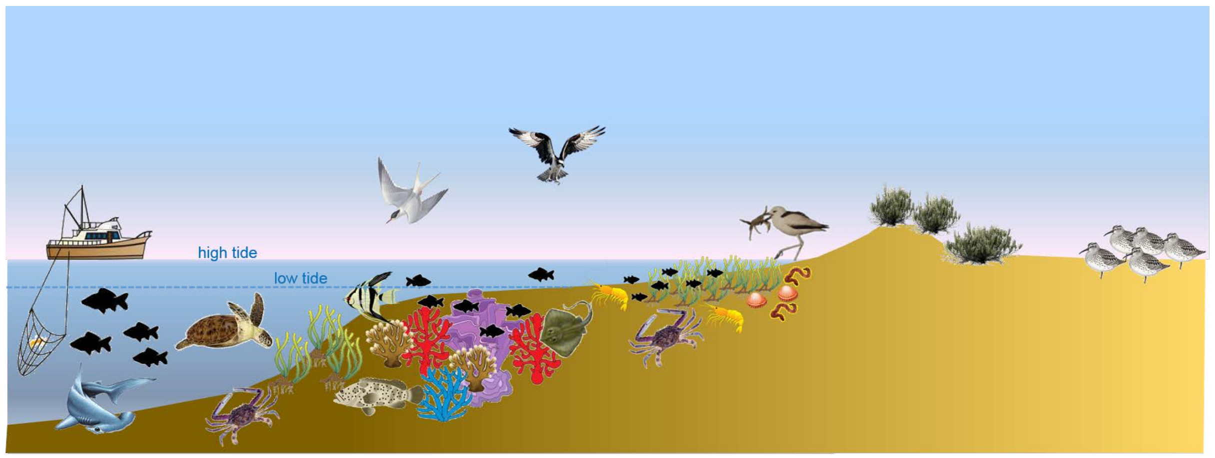


Figure 1. The three connected habitats of the Barr Al Hikman area. From left to right, the oceanic waters of the Gulf of Oman, the intertidal mudflats of the coastal zone and the coastal sabkhas of the peninsula.

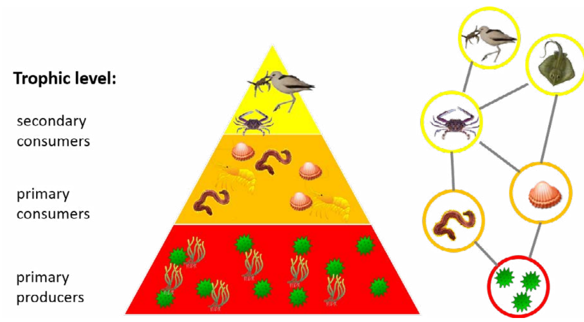


Figure 2. Left: Trophic pyramid showing the local relative biomass at each trophic level in a marine habitat (highest trophic level not included e.g. sharks, dolphins. Right: Simplified schematic example of a food web illustrated with several species found in Barr Al Hikman.

The lush plant growth lays fundament of the coastal food web. Food-webs are networks of species eating one another, in which primary producers (i.e. plants) form the basis, followed by primary, secondary, and tertiary consumers, that each make up a 'trophic level' of the network (Fig 2). In Barr Al Hikman, benthic fauna are the primary consumers as they transform plant matter into animal tissue that than becomes available for predators, such as crabs, fish and birds. Field studies by NIOZ revealed a high biodiversity in benthic fauna, with almost 100 species of gastropods, bivalves and crabs identified so far. The benthic community is dominated by three species, two marine snails (*Pirenella arabica*, *Cerithium scabridum*) and one bivalve (*Pillucina fischeriana*), that together make up over 75% of the total biomass.

Fish caught during various expeditions at Barr Al Hikman over the past decades comprised 40 species of which 32 have been identified so far. Based upon our observations and catch statistics, the shallow coastal waters can be considered an important nursery ground for several fish species. The area holds a biodiverse and relatively pristine fish community (including large rays and sharks), which appears to contrast with many other coastal areas in the world prone to overfishing. The observed richness in fish biomass and production is corroborated by the presence of high numbers of at least 20 different species of fish-eating coastal birds. Such piscivorious birds show different types of feeding strategies, including participation in multi-specific feeding associations. Moreover, during winter surveys in 1990, 2008, 2013 and 2016, up to 500.000 waterbirds, consisting of 42 species, were counted in the Barr Al Hikman area. Of these, shorebirds, that tripled in abundance since 1990, are by far the most abundant (> 80%), with 18 species exceeding 1% of their flyway population, the designation threshold for a Ramsar site. This suggests that in the Middle-East and the Asia-East African Flyways, Barr Al Hikman is a vital wintering ground for shorebirds that rely on the mudflats for feeding during low tide, and use the coastline and sabkhas for roosting during high tide. Migratory birds link this area with other ecosystems up to 10,000s of km's away (Fig 3).

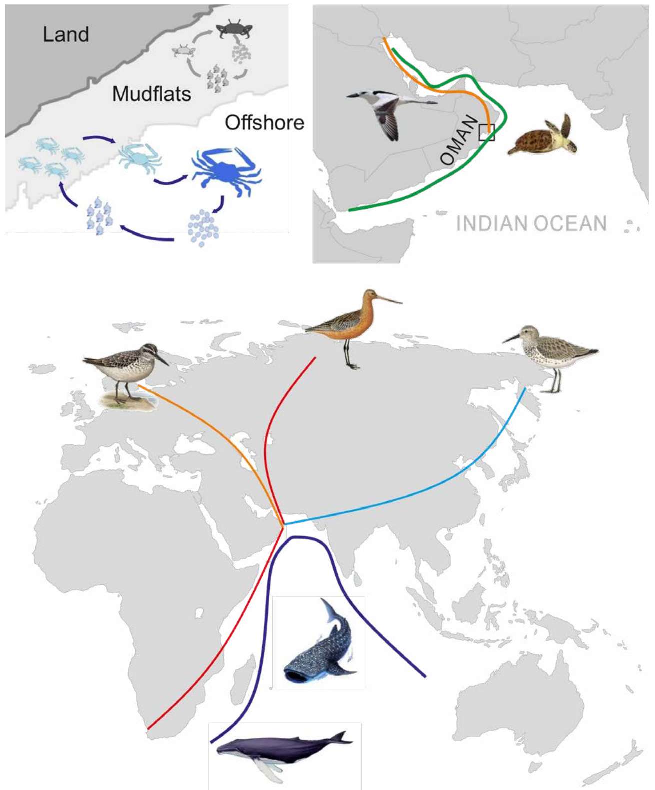


Figure 3. Examples of Barr Al Hikman and its surrounding waters as an essential link in the life cycle of crabs, fish, turtles, birds and mammals at local, regional and global scales.

It is important to note, although the Barr Al Hikman ecosystem can be subdivided into a number of habitats (e.g. sabkhas, mudflats, offshore waters), these habitats should not be considered in isolation as they are interconnected through various 'cross-habitat' interactions (Fig 1). For instance, shorebirds link the mudflats and sabkhas at a local scale by carrying nutrient-rich faeces from their feeding ground to the roosting site, and even couple ecosystems across the globe through seasonal migration. In addition, turtles have been shown to migrate over very large distances, including the turtles from the famous nesting beaching of Ra's al Hadd in Oman, an important touristic attraction, but also with waters elsewhere in the Middle East (Fig 3). Other clear examples of such spatial links are the transfer of detritus from seagrasses to the coral reefs, the nursery function of seagrass beds for juvenile coral reef fish, and tide-driven bird migration between the tidal flats and the sabkha's. These examples illustrate that it is of utmost importance to consider both local and spatial linkages when aiming to understand this ecosystem's vital functions.

This report clearly shows that the rich Barr Al Hikman ecosystem is supported by local habitats and food webs that are interconnected through multiple 'cross-habitat' interactions, locally, regionally and globally (Fig 3). Although the ecosystem is currently typified by a wealth in productivity and biodiversity, there are a number of potential threats to the natural values of the system. At present these include the increase in toxic red tides in the Gulf of Oman, increasing fishing pressure, the poaching and bycatch of turtles and possible impacts of infrastructure developments including aquaculture industry on the peninsula and oil industry offshore. The information provided by this report illustrates that science so far has only scratched the surface with respect to ecological knowledge. Such information is required to develop sustainable management solutions for Barr Al Hikman whilst facing challenges of climate change and economic activities.

Conclusions and Research Questions

Our understanding of the processes that interact in Barr Al Hikman is largely incomplete. This report gives directions and suggestions for future research. Above all, it illustrates that the fundamental links and feedbacks between the different components that interact in the ecosystem can only be understood by means of multidisciplinary and international research, including researchers from Oman and abroad. This also requires collaborations with ongoing projects in the country. Moreover, as comparative researchs is an important tool to make scientific interference, it is important to seek contacts with researchers in coastal areas all over the world.

A proper understanding of the key processes that drive the Barr Al Hikman ecosystem will require an ecosystem-level perspective that encompasses all vital ecological components and their linkages. This report provides a first insight into the habitats that make up the system and the major processes that make it function. However, we emphasize that this remains a rather superficial first glance, and does not allow for solid predictions or recommendations on how to manage the area in light of the challenges ahead. To gain such understanding, we propose well-integrated research efforts that aim to elucidate and quantify (1) habitats and species, (2) trophic interactions, and (3) connectivity.

Such an inventory would require a combination of sampling techniques, including remotely-sensed habitat surveys (e.g. by means of satellite and drone imagery) and tracking of mobile macrofauna (e.g. snails and crabs), fish, turtles and birds. These observations should be at a spatial and temporal scale and resolution that allows the capturing of relevant patterns at sufficient detail to detect relevant spatial habitat variations (e.g. small creeks) as well as trends over time (e.g. sea levels during extreme wave events). Unravelling interactions between marine coastal organisms (e.g. prey-predator relationships) and between these organisms and their environment (e.g. impacts of wave action on seagrass) requires targeted field studies and experiments. These include sediment core samplings to reconstruct past relative sea level rise, determining stable isotope signals in marine organisms to understand trophic interactions, and assessing the relationship of multi-species feeding associations of fish-eating birds with environmental conditions (e.g. tide, day light and prey abundance). The so far limited experimental efforts (e.g. exclosure and enclosure experiments with grazing snails) have proven to be feasible and fruitful. Hydrodynamic, geomorphological and ecological models can aid in the interpolation of acquired empirical data and, once validated, be used to build scenarios for different developments and management regimes.

Overall, current knowledge assembled in this report suggests that Barr Al Hikman is a relatively pristine coastal ecosystem that is internationally important with respect to its natural values and regionally important with respect to its natural resources. The uniqueness of this area with respect to its biodiversity and undisturbed food web interactions makes it an unprecedented site to get insight in how natural ecosystem function. As NIOZ, we would like to contribute to a more in-depth scientific understanding, and jointly with local counterparts build a knowledge base to support sustainable management of this area.

1 – Introduction

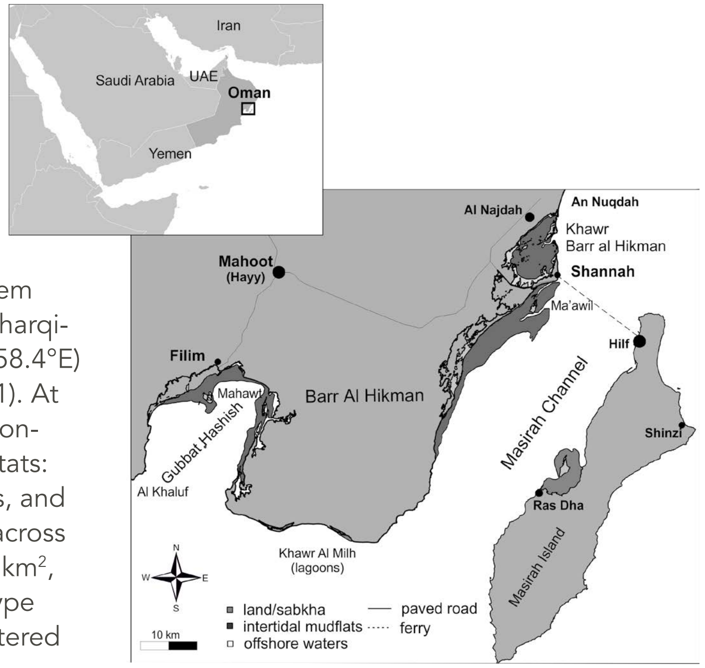


Figure 1.1. The Arabian Peninsula with Barr Al Hikman in detail, Mahoot, Al Najday and Shannah are the most important human settlements in the area.

Barr Al Hikman

Barr Al Hikman is a large coastal ecosystem located within in the Al Wusta and Ash Sharqiyah region, Sultanate of Oman (20.6°N, 58.4°E) and bounded by the Arabian Sea (Fig 1.1). At present, the Barr Al Hikman ecosystem consists mainly of three interconnected habitats: (1) coastal sabkhas, (2) intertidal mudflats, and (3) offshore waters. The sabkhas stretch across the peninsula and cover an area of 1400 km^2, the largest collection of this landscape type in Oman. Coastal dunes, along with scattered small mangrove stands of Avicennia marina, form a narrow 5-20m fringe between the sabkhas and the intertidal mudflats, and are intersected by several small creeks. The intertidal mudflats of about 190 km^2 form the link between the coastline and the offshore waters and are typified by bare mudflats and seagrass meadows, intertidal pools and channels. The waters surrounding the intertidal mudflats contain seagrass beds and coral reefs.

Barr Al Hikman is renowned for its abundant birdlife, turtle habitat, and the passage of dolphins and whales around Masirah Island. It has an exceptionally large diversity of marine life. The area also serves as a keystone habitat for economically valuable species such as fish and crabs.

The importance of Barr Al Hikman for many species of waterbirds, and marine animals including turtles and whales, was already recognized in the 1970s and '80s (e.g. Gallagher and Woodcock, 1980; Ross, 1985; Salm et al., 1993; Green et al., 1994). In the 1990's research continued with a basic but very valuable description of habitat-forming foundations species such as coral reefs, seagrass meadows and mangroves (Fouda and Al-Muharrami, 1995; Jupp et al., 1996; Mohan and Siddeek, 1996; Claereboudt, 2006). This work also resulted in recognizing Barr Al Hikman as an important nursery area for shrimps (Mohan and Siddeek, 1996). The interior of the peninsula received attention from geomorphologists who described the uniqueness of the pristine arid environment (Mettraux et al., 2011). Although the site was studied regularly, it was not until 2007 that a group of scientists started visiting Barr Al Hikman on a yearly basis. The main objective of their research was to understand the ecosystem functioning of the area and collaborate with local counterparts (e.g. The Ministry of Environment and Climate Affairs, Sultan Qaboos University, The Environmental Society of Oman, see Appendix 1).

This report reviews the current knowledge of the ecosystem and explores future research challenges associated with the area. The aim of this report is to provide a general description of ongoing research and discuss future challenges, rather than to describe the ecosystem in detail.

The report starts with reviews of the abiotic, long-term processes that act upon the area, including geology (Chapter 2), large scale hydrodynamics (Chapter 3) and dust deposition (Chapter 4) followed by a description the geomorphological and hydrological basis of the intertidal area (Chapter 5), followed by The second part of the report describes in the ecology of Barr Al Hikman. Thereby we follow a bottom-up approach, starting with characterising the primary production (Chapter 6) and primary consumers (Chapter 7) of the area. Higher trophic levels are covered in five separate chapters, dealing with fish (Chapter 8), benthic eating shorebirds (Chapter 9), piscivorous shorebirds (Chapter 10), sea turtles (Chapter 11) and offshore seabirds and marine mammals (Chapter 12). The complexity of the food web is discussed in a final chapter (Chapter 13). The chapters are composed using a 'factsheet' format with an introduction, a current knowledge section, a discussion on the most important knowledge gaps and suggestions for future research.

In the final part of the report, the various chapter's suggestions are assimilated into a proposal for long-term field observations, field studies, modelling efforts and field experiments. This report proposes that local- scale research work be done in the context of the broader West-Indian Ocean regions well as within the context of an international network of globally important coastal wetlands.

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2 – Relative sea level changes, differential uplift and extreme waves

Part I: Environmental conditions

2 – Relative sealevel changes, differential uplift and extreme waves

Paolo Stocchi

Introduction

Desert landscapes and saline soils are the main characteristics of the present coastal and inland areas of Barr Al Hikman and of Oman in general. The coastal sabkhas (salt areas) of Barr Al Hikman are the most outstanding examples of the evaporation-dominated conditions that have shaped the local landscape during the last few millennia (see the red rectangle of Fig 2.1). The current geomorphological and environmental settings of the Barr Al Hikman peninsula are, in fact, the end results of peculiar geophysical processes that modulated the local sea-level changes during and after the melting of the Last Glacial Maximum ice sheets (LGM, ~21.000 years Before Present). This chapter describes the role of long-term sea-level change, crustal deformations and episodic marine inundations in forming the present geomorphology of the Barr Al Hikman peninsula.

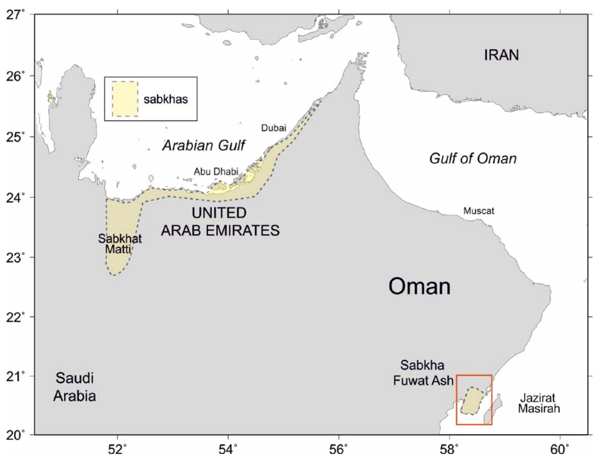

Figure 2.1. Location of eastern Arabian sabkhas (in yellow). The red rectangle locates Barr Al Hikman study area (reproduced from Mettroux et al., 2011).

Knowns

The sabkhas of Barr Al Hikman peninsula
The Barr Al Hikman peninsula is approximately 35 km wide (from East to West) and 40 km long (from South West to North East; Glennie, 2005). With the exception of two distinct elevated areas that are 30-40 m above mean sea level (hereafter msl), the peninsula is characterized by a relatively low-lying topography (1-15 m of altitude). Approximately 1500 m^2 of the low-lying topography are covered by sabkhas (Mettraux et al., 2011). From a geological point of view, sabkhas are shallow water carbonate/evaporate systems that form and develop under arid climate conditions as a consequence of the interplay between (i) strong evaporation, (ii) input of saline water from the sea and from the ground (saline wedge intrusion), (iii) input of continental freshwater from the ground, (iv) rainfall and (v) spikes of early-morning high relative humidity (Mettraux et al., 2011). The sabkhas of Barr Al Hikman can be divided into coastal or continental (inland) based on elevation, distance from the sea, geomorphology and hydrology. Coastal sabkhas are found between 1 and 5m above msl and are mostly fed by sea water as a result of floodings due to high sea levels (high tides, storm surges) and to the related saline groundwater intrusions. Continental sabkhas are found up to 15 m above msl and are mostly fed by fresh groundwater, rain and condensation. Sabkhas can be further differentiated into active (modern) or fossil (old), based on their age and functionality. Active sabkhas are characterized by the occurrence of saline/fresh water influx, evaporation, salts precipitation, as well as living organisms such as halophytes plants. Fossil sabkhas, on the other hand, are merely salts and evaporites deposits that are found nowadays at elevated positions (1-10 m above msl) and in the proximity of outcrops of shallow marine fossils (bivalves assemblages). Unfortunately the lack of precise dates for the fossil deposits does not allow for a precise chronology of events. However, speculations based on local geology and palaeontology suggest that the older deposits might be of Pliocene age (5,3 to 2,5 Million of years BP) or of Pleistocene age (Last Interglacial, ~115,000 to 130,000 years BP), and therefore likely related to higher-than present global mean sea level (Raymo et al., 2011). The younger fossil material on the other hand, might record a transition from the late Pleistocene (after ~21,000 years BP) throughout the Holocene (the last ~12,000 years). The fossil material that is found nowadays between 1 and 5 m above msl is likely of Holocene age, indicating a marine transgression that was related to a higher-than-present sea level, which was then followed by a continuous drop throughout the last ~6,000 thousand years.

Holocene relative sea-level changes

The long-term sea-level change that is required to explain the formation and preservation of sabkhas at Barr Al Hikman is obviously at odds with the global mean sea-level trend that characterized the Holocene. The latter is affected by a climatic optimum and follows a period of relatively rapid melting of the large continental ice sheets that covered significant portions of the northern and southern hemispheres during the Last Glacial Maximum (LGM, ~21,000 years BP). During the LGM, in fact, the Greenland and Antarctic ice sheets were larger and thicker than they are today, while North America and Eurasia were partially covered by large and thick ice sheets.
The theory of eustasy states that any land-based ice mass variation would be accompanied by an instantaneous sea-level change that is the same everywhere, i.e. the global ocean behaves like a bathtub with respect to fluctuating ice sheets. (Suess, 1906; Rovere et al., 2016b). Eustasy, in fact, assumes that the Earth is rigid (non deformable) and that gravity is absent. Therefore, eustasy simply follows from the principle of mass conservation. Accordingly, during the LGM, an amount of water equivalent to 130-140 m of eustatic sea-level drop was stored in form of continental ice sheets in the northern and southern hemispheres (Milne, 2009). The global warming that followed the LGM triggered the melting of the ice sheets, which in turn resulted in a global eustatic sea-level rise. By the beginning of the Holocene (~12,000 years BP), 30-40 m of eustatic sea level was still stored in the form of ice sheets. The latter were almost completely melted by ~8,000 years BP, when only few meters of eustatic sea level where left on the continents and eventually released until 2,000 years BP. The theory of eustasy, therefore, cannot explain the sea-level drop that is observed at Barr Al Hikman during the last ~6,000 years. However, before looking for local or regional geologic processes that are related to tectonics geodynamics and that could explain a possible crustal uplift in the area, one should discard the eustatic approximation and explicitly account for solid Earth deformations and gravitational perturbations under surface loading variations.
According to the theory of glacial- and hydro-isostatic adjustment (GIA, also known as post glacial rebound, i.e. PGR), any continental ice-mass variation (either growth or shrink) results in isostatic disequilibrium of the solid Earth (Rovere et al. 2016b).
The removal of ice from the continents and its redistribution in form of meltwater in the oceans triggers land uplift in the formerly glaciated areas and sea-bottom subsidence in the oceans. Accordingly, ice-sheets fluctuations result in relative sea-level (RSL) changes because both land and mean sea surface change with respect to each other (Rovere et al. 2016b). The solid Earth

deformations accompany and follow the ice sheets fluctuations and exponentially decay in time as a function of the mantle viscosity (Spada and Stocchi, 2007). Furthermore, ice-mass variations and the related solid Earth deformations operate as density anomalies and contribute to vertical perturbations of the geoid, which is the equipotential surface of gravity, which in turn corresponds to the mean sea surface. In the proximity of a melting ice sheet the mean sea surface drops in response to the decreasing gravitational pull, while it rises more than the eustatic far away from the ice sheets (Farrell and Clark, 1976; Spada and Stocchi, 2007). This process is known as self-gravitation and is a fundamental component of the whole GIA process, in particular in the ice-proximal locations.
Although Oman is located in the far-field with respect to the continental ice sheets, the local GIA signature results in a significant departure from eustasy that cannot be neglected. Fig 2.2 clearly illustrates this important aspect. Here two slightly different post-LGM ice-sheets chronology are compared: ICE-5G (Peltier, 2004) and ICE-6G (Argus et al., 2014; Peltier et al., 2015). The black and red dashed curves represent the eustatic sea-level curves according to ICE-5G and ICE-6G, respectively. According to eustasy, sea level cannot exceed the present-day elevation during the last 8,000 years. The solid curves, instead, show the full GIA solution obtained by solving the gravitationally self-consistent the Sea Level Equation (Spada and Stocchi, 2007). The local GIA signature results, for both models, in a late Holocene RSL highstand (up to 2 m above msl), followed by an almost linear RSL drop. The predicted RSL highstand and the following RSL drop are consistent with the observed elevated shallow marine fossils and evaporites deposits (Fig 2.3a, b).

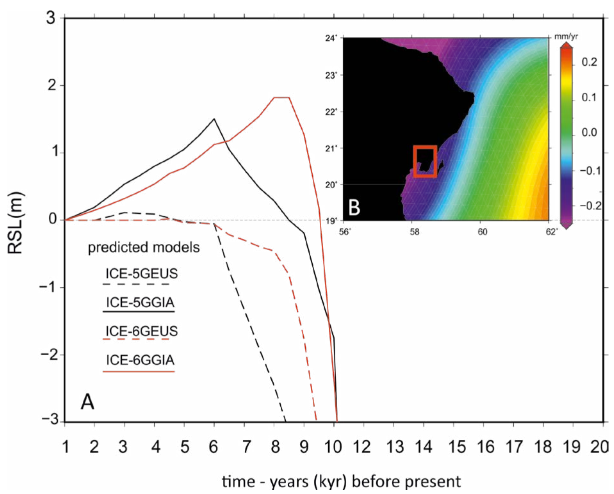

Figure 2.2. Predicted Holocene RSL curves and present day rates of RSL change at Barr Al Hikman. The horizontal axis represents time per 1000 years (kyr) (from past to present, respectively from right to left). The vertical axis represents RSL elevation above present level. A) Dashed curves show the eustatic sea-level change according to ICE-5G (black) and ICE-6G (red); solid curves show the GIA-modulated RSL change for ICE-5G and ICE-6G, predicted by these models. B) present-day rates of RSL change according to ICE-5G.


Figure 2.3 a) elevated late Holocene shallow-marine fossils (image by J. van de Kam) and b) evaporites gypsum deposits.(image by J. de Fouw)

Two GIA-related processes are responsible of this peculiar RSL trend. The first process is called continental levering and is the uplift of coastal land in response to the lithospheric tilt caused by meltwater loading on the bottom of the central ocean areas (Farrell and Clark, 1976; Stocchi and Spada, 2007). The latter, in fact, are affected by subsidence and, as a consequence, the upper mantle material flows from the bulk of the ocean basins towards the surrounding continents eventually causing uplift. The second process is the so-called equatorial ocean syphoning and consists of the migration of ocean water towards northern and southern hemisphere's narrow and circular areas that surrounded the LGM ice sheets (Mitrovica and Peltier, 1991; Stocchi and Spada, 2007). These areas, in fact, were uplifted during the LGM and are now subsiding.
The two processes described here dominate the present-day GIA-induced rate of RSL change along the coasts of Oman, where a RSL drop of 0.1 to 0.3 mmyr^{1} is expected (Fig 2.2a). The rates of RSL drop decrease towards open sea until the zero line (i.e. eustatic) is met (green color). Offshore of the zero line, the sign of GIA fingerprint changes because of meltwater-induced subsidence.
Overall, GIA is capable of explaining the formation of sabkhas at Barr Al Hikman. However, the salts and evaporites deposits that are found between 5 and 15 m above msl might require and additional uplift. Alternatively, those deposits are not from the Holocene, but were created further back in time, most likely during warmer interglacial, when the Antarctic Ice Sheet might have been significantly smaller than today (Pliocene or Pleistocene).

Regional differential uplift

Marine terraces are shallow marine and wave-dominated stretches of coasts that are nowadays found at elevated positions with respect to msl (Rovere et al., 2016a). Therefore, marine terraces witness local either land uplift or sea-level fall due to glaciations or a combination of the two. In other words, marine terraces are the most prominent geomorphological effects of local RSL drop. The occurrence of staircase of elevated marine terraces (up to 350 m above msl) at Ras al Hadd, i.e. along the Arabian Sea in Oman, suggests recent uplift of a crustal block in the northeast of the Arabian Peninsula (Fig 2.3; Hoffmann et al., 2017). These observations indicate an ongoing uplift in the range of less than 1.0 mmyr^{1}, although it is more likely that the uplift occurred stepwise in time, rather than linearly. Overall, the observed uplift is at odds with the regional tectonic settings, which would favour subsidence rather than uplift (see Fig 2.3 where the Makran Subduction Zone, MSZ, is located by the black triangles).

Hoffman et al. (2017) propose that the uplift is likely the result of serpentinization, i.e. a geochemical process that consists in the hydration of mantle rocks. The latter would be responsible for a decrease in density (paired by an increase in volume). As a result, the increase in buoyancy would lead to deformations and crustal uplift that eventually shows up in form of local to regional RSL drop. Hoffmann et al. (2017) argue that the uplift is differential, i.e. a gradient is expected from North to South, but no evidences are at the moment available for the area surrounding Barr Al Hikman.
The differential uplift caused by serpentinization might add to the GIA-driven signal and result in a stronger local to regional RSL drop. The latter, therefore could partially balance, at least for a while, the on-going and future sea-level rise due to global warming.

Extreme waves, typhoons and tsunamis

Current and future sea-level rise pose a serious threat for low-lying coastal areas such as the

Barr Al Hikman peninsula. Even low rates of sea-level rise, i.e. once the buffering effects of GIA and differential uplift are accounted for, could increase the rates of coastal erosion and the sea-water intrusion in the coastal aquifers. The reason for this is to be found in the extreme episodic wave events that, under slightly higher sea levels, could result in catastrophic consequences.

Coastal geomorphological and archaeological evidences along the norther coasts of Oman suggest that the Holocene was characterized by the occurrence of extreme wave events. The latter have deposited material that is nowadays preserved in the onshore stratigraphic records (Hoffmann et al., 2015). Extreme wave-events may be generated by storms and tropical cyclones and may result in significant storm surges along the coasts. It is however not clear if the storms and typhoons that generate in the northern Indian Ocean can reach the coast of Barr Al Hikman.

Numerous catalogues of past tsunami events have been published for the Northern Indian Ocean (Hoffmann et al., 2015). However, the recurrence interval of tsunamis within the Arabian Sea is currently regarded as speculative. Recent results of comprehensive mapping and analysis of extreme wave deposits of an archaeological site near Ras al Hadd (Fig 2.4), suggest that the Early Bronze Age site was inundated 4,450 years BP. It is concluded that the causative event must have been a tsunami that was most likely generated within the Makran Subduction Zone (MZS, see Fig 2.4). Again, as for the storm surges, it is not clear if tsunamis could actually reach Barr Al Hikman peninsula.

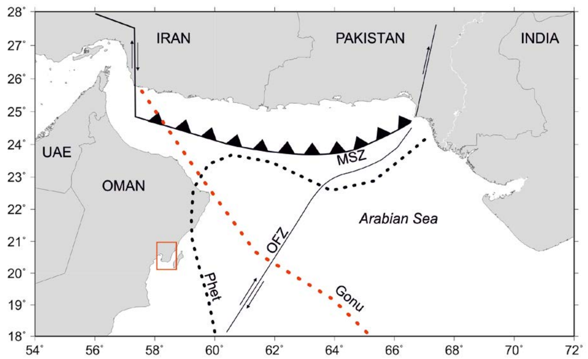

Figure 2.4. Plate tectonic settings and tracks of tropical cyclones. The black triangles locate the Makran Subduction Zone (MZM). The black thin line locates the Owen Fracture Zone (OFZ) and the relative horizontal motion of plates (arrows). The red and black dots locate the tracks of tropical cyclones Gonu and Phet respectively. The red box locate the Barr Al Hikman peninsula. This figure is adapted from Hoffmann et al. (2015).

Unknowns

There is a general lack of quantitative evidence (either geomorphological or instrumental) of vertical crustal deformations for the Barr Al Hikman peninsula. Furthermore, the lack of precise dates of the elevated fossil and salts deposits prevents a reliable calculation of either local vertical motions or long-term climate-driven and GIA-modulated RSL changes. Paleo sea-level indicators that could constrain the post-LGM and Holocene RSL changes have never been analysed and interpreted. As a result, there are no available GIA-modelling studies. Similarly, the evidences of past tsunamis and extreme waves are too sparse and not well dated to be used as boundary conditions for ocean waved and tsunamis modelling. There are only three available tide gauge stations, but the time-series are too short to derive a long-term trend of sea-level change that can be related to the human-induced global warming.

Conclusions and Research Questions

The Barr Al Hikman peninsula is an extremely interesting natural lab for understanding the past RSL changes and their consequences to the coastal ecosystems. The available paleo RSL indicators could constrain the ice-sheets fluctuations that occurred since the Pliocene. Also, the sabkhas are extremely interesting features that could provide more insights into the relationship between sea level and ground water migration (saline wedge intrusion). Therefore we suggest to set up:

- Elevation and dating (Radiocarbon, Uranium-Thorium, etc.) studies of past RSL indicators. The available paleo RSL indicators could constrain the past ice-sheets fluctuations that occurred since the Pliocene and shed light on the behaviour of the Antarctic Ice Sheet during warmer climates;
- Field studies aimed at understanding the relationship between fluctuating sea level (tides, storm surges etc) and ground water migration (saline wedge intrusion);
- Positioning of permanent GPS stations for measuring the crustal vertical deformations (regional differential uplift etc.);
- Positioning of wave buoys offshore for understanding the wave climate;
- Positioning of tide-gauges and/or bottom pressure recorders for measuring RSL changes on the short- and long-time scale;
- Geological and hydrological in-situ investigation of the sabkhas for understanding of physical and geochemical processes that regulate the salts deposition. This might shed light on similar larger-scale processes that occurred in the geological past of the Earth, i.e. the Messinian Salinity Crisis of the Mediterranean Sea (5 to 6 Million years BP);
- Development of numerical models aimed at coupling ocean dynamics, sea level, groundwater migration sediment transport and coastal geomorphology.

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3 – Oceanography

3 – Oceanography

Eelke O. Folmer & Roeland A. Bom

Introduction

The oceanographic conditions are important for the ecological functioning of coastal areas (Sheppard et al. 1992). This chapter provides a brief overview of what is known with regards to hydrography, ocean circulation and upwelling in the Arabian Sea from the perspective of the coastal ecology at Barr al Hikman.

Knowns

Hydrography

The Arabian Sea lies in the north-western part of the Indian Ocean. It is bounded to the west by the Horn of Africa and by Yemen and Oman on the Arabian Peninsula, to the north by Iran and Pakistan, to the east by India, and to the south by the remainder of the Indian Ocean (Fig 3.1). Most of the Arabian Sea has depths exceeding 3000 m. Only the coastal waters of Oman, Pakistan and India are relatively shallow (below 200 m). However, the continental shelf along the Arabian Peninsula is rather narrow.

The Arabian Sea was formed roughly 50 million years ago when the Indo-Australian plate collided with the Eurasian plate during which the Himalaya mountain range was also formed. In the Arabian Sea lies the Carlsberg ridge, a divergent tectonic boundary between the African and Indo-Australian plates. The Carlsberg ridge is seismically active (Sheppard et al. 1992). The Arabian Basin is separated from the Gulf of Oman Basin by the Murray Ridge, a narrow, seismically active ridge that extends northeast to southwest where it meets the Carlsberg Ridge (Fig 3.1).

Ocean circulation and upwelling

The Arabian Sea is strongly influenced by the Asian weather system which causes the Indian ocean monsoons and ocean circulation (Fig 3.2). The most relevant element of the Indian Ocean circulation for the Arabian Peninsula coast is the Somali Current. The Somali Current is a boundary current along the coasts of Somalia and Oman. The current is propelled by the monsoon. In the period June-August the monsoon winds are south-westerly. The warm south-westerly monsoon moves the coastal waters north eastwards thereby creating coastal upwelling. In the period December-February the monsoon winds are north-easterly. The North-east monsoon causes a reversal of the Somalia Current and coastal waters then flow in a south-westerly direction. Upwelling at the coastal region of Oman is nearly continuous but especially during the south-westerly monsoon, strong upwelling brings cold and nutrient rich water to the Oman region resulting in periods of high biological productivity (see Chapter 6).

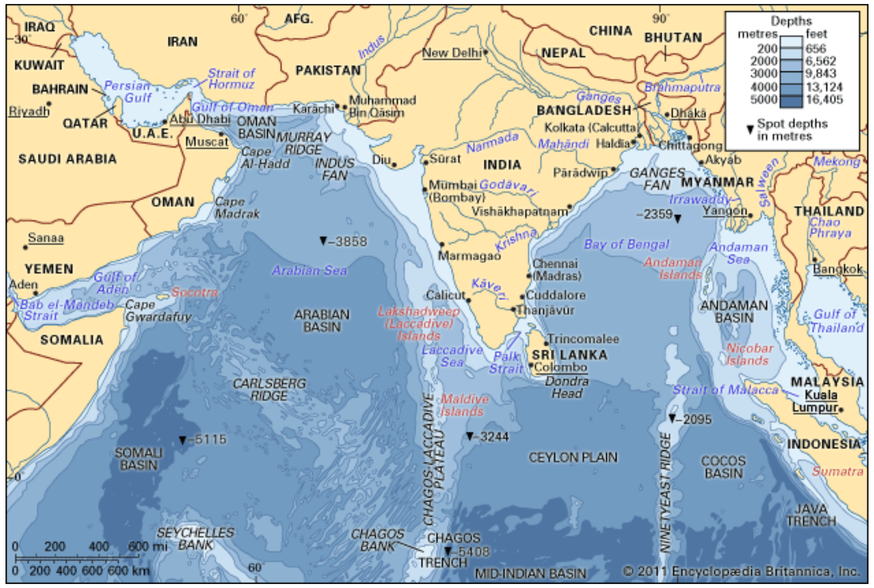

Figure 3.1. Arabian sea Source: Encyclopaedia Britannica

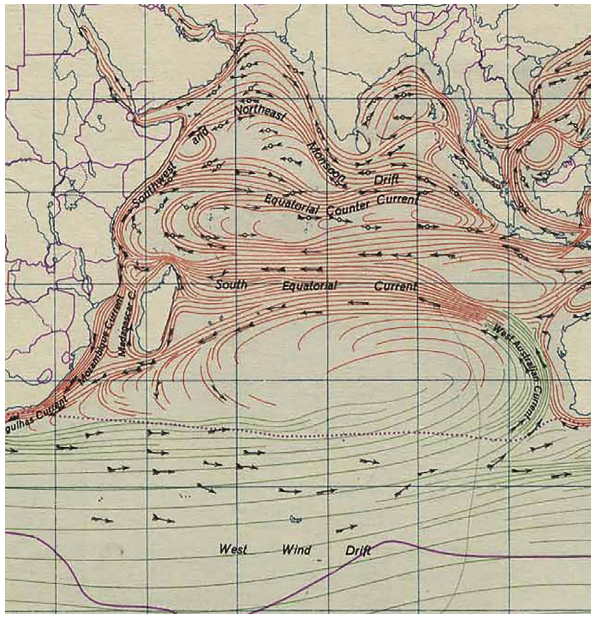

Figure 3.2. Somali Current (source: www.lib.utexas.edu/maps/world_maps/ocean_currents_1943.jpg)

The nutrient rich waters from the Antarctic region are brought to the Arabian Sea by means of a deep flowing current. After a period of intense upwelling during the south-westerly monsoon, primary productivity decreases. Analysis of the variability of the Somali current by means of a numerical model of wind-driven circulation in the Indian Ocean shows that observed current variability in the Arabian Sea is mainly due to variability in winds (Luther and O'Brien, 1989). An important research question with regards to the ecological functioning of the intertidal flats at Barr Al Hikman concerns the level of influence of the upwelling on the coastal zone.

Unknowns

Models exists that are able to simulate upwelling phenomena at a relatively coarse levels (e.g. Izumo et al. 2008). On the basis of bathymetric maps at a relatively fine spatial resolution, further insight into the impact of coarse scale variability on local scale variability can be obtained. For instance, the role of the continental shelf in the upwelling phenomena can be studied in detail. It is important to measure several variables to tune and validate possible hydrodynamic models.

Conclusions and Research Questions

General information about the hydrography and ocean circulation and the impact on the biological productivity is available. An important research question with regards to the ecological functioning of the intertidal flats at Barr Al Hikman concerns the level of influence of the upwelling on the coastal zone.

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4 – Arabian dust deposition in Oman and its potential environmental impacts

4 – Arabian dust deposition in Oman and its potential environmental impacts

Jan-Berend W. Stuut

Introduction

Mineral dust is known to affect marine and terrestrial ecosystems by the supply of both nutrients from which ecosystems may profit (e.g., Yu et al., 2015b) as well as pathogens that may cause diseases (e.g., Griffin, 2007; Shinn et al., 2000).
Modern dating techniques have allowed reconstructions of sediment (re)distribution patterns through the Late Quaternary, showing that the Arabian Gulf served as a source of sediments for large parts of the Arabian Peninsula during sea-level lowstands (Glennie et al., 2011; Pease and Tchakerian, 2014). Sediment redistribution presently still takes place by the prevailing NNW (Shamal) and SW (summer monsoon) wind systems. Most of the inferences on wind-blown dust that was blown into the Indian Ocean were made on deep-sea sediments (Clemens et al., 1996; Clemens and Prell, 1990; Prins et al., 2000a; 2000b; Prins and Weltje, 1999) and relate to Pleistocene reconstructions of the Asian monsoon. In addition, on-land studies have reconstructed provenance of dune sands and their general transport directions (Glennie et al., 2011; Pease and Tchakerian, 2014; Pease et al., 1999).
There are multiple dust sources in the Middle East and emission, transport, and deposition may vary, depending on rainfall in the dust sources as well as seasonal changes in wind patterns (Fig 4.1a). The majority of dust that is blown into the Arabian Sea is carried there by the year-round north-northwestern Shamal, which blows dust from the Tigris-Euphrates basin (fig 4.1b), whereas in summer, the southwest monsoon also carries in dust from eastern Africa (fig 4.2, Bou Karam Francis et al., 2017). Although there may be little seasonal variability in the input of dust from Iraq and Saudi Arabia, there appears to be a strong inter-annual variability, which is related to the El Nino – Southern Oscillation (ENSO; Yu et al., 2016). In addition, throughout the recent past, a dramatic erosion of agricultural lands has led to increased dust emissions from 2007-2013 (Notaro et al., 2015). Observations of dust transport and deposition into the Arabian Gulf and its marine-environmental consequences were suggested by Hamza et al. (2008; 2011) but in terms of actual consequences of dust deposition, only some inferences were made. In the "grey literature" (Herring, 2002) there is a reference to a widespread fish kill in the Gulf of Oman, which was related to dust deposition. Again: the impacts of dust may be both positive (stimulating phytoplankton growth, but potentially also fertilisation of sea grasses) and negative (causing toxic algal blooms or dispersion of pathogens).

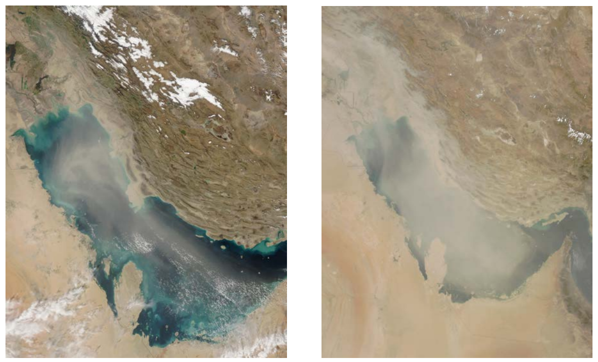

Figure 4.1 a) dust outbreak on 19 February 2017, b) dust outbreak on 31 July 2009. Satellite images courtesy of NASA earth observatory website.

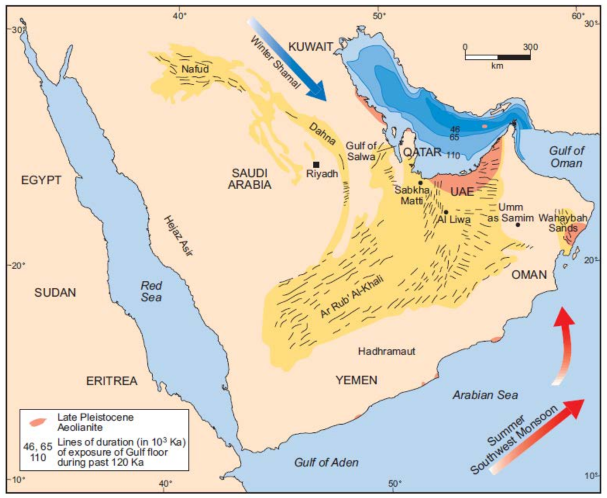

Figure 4.2. Map of the study area (from Hamza et al., (2011)) with general wind directions and examples of dust storms related to the north-northwestern Shamal winds.

Knowns

Large amounts of dust are deposited in Oman and on the Oman continental slope. Quantities are estimated on the basis of satellite images and are in the same order of magnitude as those derived from the World's largest single source of dust: the Bodélé Depression in Chad (Bou Karam Francis et al., 2017). Dust loads during single outbreaks may be up to several Million Tons.
Droughts in the Tigris-Euphrates Basin in combination with poor land-use management have led to increased amounts of dust emissions throughout the recent past (Notaro et al., 2015). In addition, breaking of desert crust in the Gulf War also led to increased dust emission (Linden et al., 2004). How much of this "anthropogenic" dust is polluted (e.g., by fossil-fuel- and agricultural side-products/pesticides) is unknown.

Unknowns

Although estimates of dust emissions do exist, they are suffering from large error bars due to side effects such as the atmosphere's moisture content and clouds (e.g., Yu et al., 2015a). Furthermore, (Time series of) deposition fluxes of Arabian dust deposited in Oman do not exist.

The impacts on terrestrial and marine ecosystems of dust depositions in Oman are not known. It has been hypothesized that the nutrients that are carried into the Indian Ocean may have a large effect on the Ocean's biogeochemistry and biology, which could be both positive (e.g., Hamza et al., 2011) as well as negative (e.g., Herring, 2002).

Scale of importance

The Indian Ocean plays a key role in the earth's ocean circulation, which distributes energy and nutrients; waters from the deeper part of the basin are upwelling on the Indian continental slope as well as off Oman. As these upwelling waters contain a lot of nutrients, they form rich fishing grounds on which millions of people around the entire Indian Ocean are depending.

Conclusions and Research Questions

Mineral dust affects marine and terrestrial ecosystems by the supply of nutrients and pathogens. The amounts and fertilising/polluting role of metals and nutrients added by mineral dust are unknown and need to be quantified. Therefore it is recommended to:

- Monitor dust fluxes of mineral dust deposited in Oman:
- Using satellite-imagery archives, a time series of dust-emission, transport, and deposition can be estimated for the past few decades (earliest satellite observations were made with the Coastal Zone Color Scanner (CZCS) since the mid 1970's);
- Using new dust-sampling stations, the amount and composition of dust deposited in Oman can be characterised and quantified. We have set up a similar station that registers dust transport at the source in Iwik, Mauritania, since

2013 (Fig 4.2). Two 3-m high masts have been set up and equipped with five so-called MWAC (Modified Wilson And Cook, Goossens et al., 2000) passive dust samplers at 50-cm intervals. Every month, a local collaborator exchanges the bottles of the samplers, thus establishing a time series of dust transport. A similar dust-sampling scheme should be set up in Oman.

- Set up a marine monitoring program to study the marine environmental impacts of dust deposition. This can be done e.g., by using moored instruments collecting time series of both mineral dust as well as its consequential marine environmental impacts (e.g., potential increased productivity).

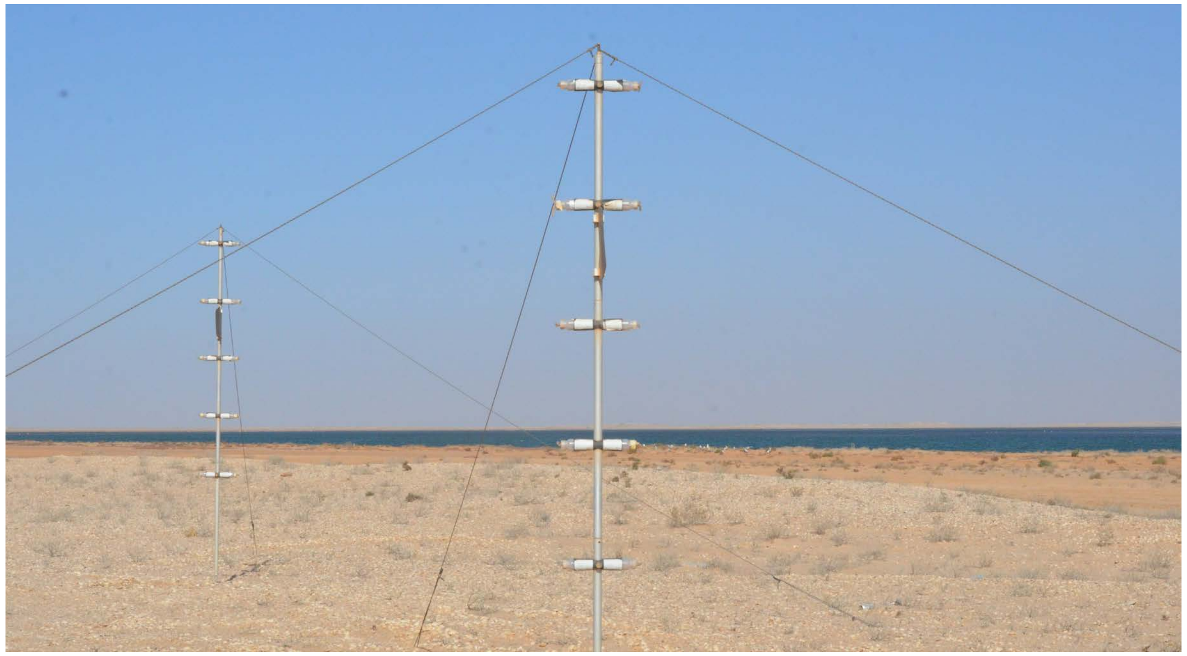

Fig 4.2: Dust sampling station in Iwik, Mauritanian coast. Two masts with MWAC samplers at 90, 140, 190, 240, and 290 cm above surface, sampling dust at a monthly resolution. A meteorological station monitors the meteorological conditions at the site, after which dust transport can be related to e.g., wind speed and direction (Friese et al., 2017)..(image by J. ten Horn)

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5 – Geomorphological and hydrodynamical basis of Barr Al Hikman

5 – Geomorphological and hydrodynamical basis of Barr Al Hikman

Roeland A. Bom & Eelke O. Folmer

Introduction

The hydrodynamic and geomorphological conditions at intertidal flats are important determinants of the abundance and distribution of species and the ecological functioning of intertidal communities in general (e.g. Compton et al. 2013 and Folmer et al. 2017). Tropical coastal intertidal areas typically form heterogeneous landscapes with coastal sabkhas, mangroves, dunes, mudflats, seagrass beds, reef structures and gully networks. These landscape structures directly influence water movements, soil structure and the physical and chemical properties of an area and by that the spatial distribution of primary consumers and higher trophic levels. Therefore, understanding the geomorphology of Barr Al Hikman is an important aspect in understanding the ecosystem as a whole.

Knowns

Geomorphology & habitat characteristics
The intertidal mudflats are characterized by a patchwork of barren areas, alternating with pools and seagrass beds that are intersected by many smaller and larger gullies. The main seagrass species that occur in the area are *Halodule uninervis* and *Halophila ovalis* (Fouda and Almuharrami 1995; Jupp et al., 1996; de Fouw et al., 2017; Fig 5.1), and occasionally *Syringodium isoetifolium* and *Thalassia hemprichii*. Raised fossil reefs and reefs formed by the polychaete *Pomatoleios kraussiireefs* (Fig 5.2) are found scattered throughout the intertidal zone. A number of deep gullies, possibly formed after periods of heavy rainfall (Mettraux et al., 2010), intersect the mudflats reaching into the sabkhas.

Figure 5.2. Reefs formed by constructions of polychaeta *Pomatoleios kraussiireefs* are found scattered throughout the intertidal zone.(image by J. van de Kam)

Figure 5.1. A typical view on the mudflats of Barr Al Hikman, with seagrass beds on the left and bare patches on the right. (image by R. Bom)

The morphology of the mudflats at Barr Al Hikman was constructed by mapping the elevation of the mudflats a number of times over the period 2008-2011. The surveys als included measurements of sediment characteristics and the mapping of reefs and seagrass densities. Some results of these surveys are presented in Fig 5.3.

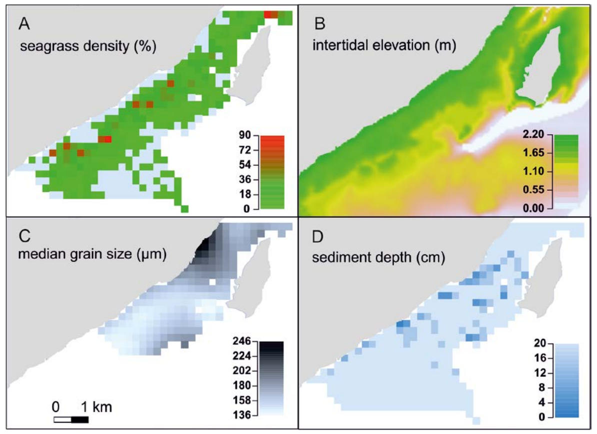

Figure 5.3. Morphology of the intertidal flats at Barr Al Hikman (study area south of Shannah). (A) Seagrass density visually mapped (Braun-Blanquet, 1932) in November 2012 on a 250*250 m grid. (B) The tidal elevation after a digital elevation model developed by Molenaar (unpublished). (C) Median grain size of the sediment, mapped in November 2011 on a 250*250 m grid. (D) The penetrability of the soil. Reef outcrops occur at locations with low penetrability.

There are also technical developments with regards to unmanned aerial systems (UAS, drones) in combination with various types of instruments that make it possible to create detailed bathymetric maps of the coastal area including intertidal flats. Especially the combination with laser altimetry (Lidar) is promising. However, more standard RGB camera's (for colour imaging) in combination with electronic control points can also be used to measure elevation (based on the structure from movement approach). Furthermore, it is possible to use UAS with multispectral sensors to map the structure of the mudflats and possibly obtain information about the sediment composition. A test flight with a multispectral camera in 2017 shows the potential of mapping intertidal mudflats using a multispectral camera (Fig 5.4).

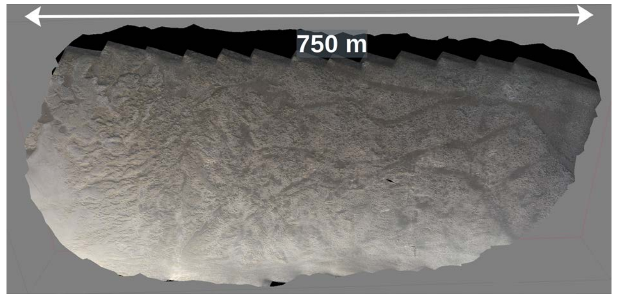

Fig 5.4. Orthomosaic of intertidal mudflat at Barr Al Hikman. The images were recorded with a Parrot Sequoia multispectral camera in 24 February 2017.

Hydrodynamics
The tidal cycle at Barr al Hikman is relatively well described. The cycle is complex and consists of a mixture of diurnal and semidiurnal tides (Fig 5.5). There are only a few tidal gauges along the coast of Oman which makes it difficult to obtain detailed and local information about the impact of wind on the tides. With the development and use of hydrodynamic models it will be possible to obtain detailed information regarding flooding and exposure of tidal flats.

Unknowns

Many of the hydrodynamic forces acting on the intertidal mudflats remain unknown. This includes floodings, currents and waves. There is virtually no knowledge about the interaction between geomorphological and hydrographical conditions and the effects on primary and secondary consumers (benthic invertebrates, avian and marine vertebrates, see chapter xx). Temporal variation of tidal elevations (gullies), reef structures and sediment characteristics are unknown.

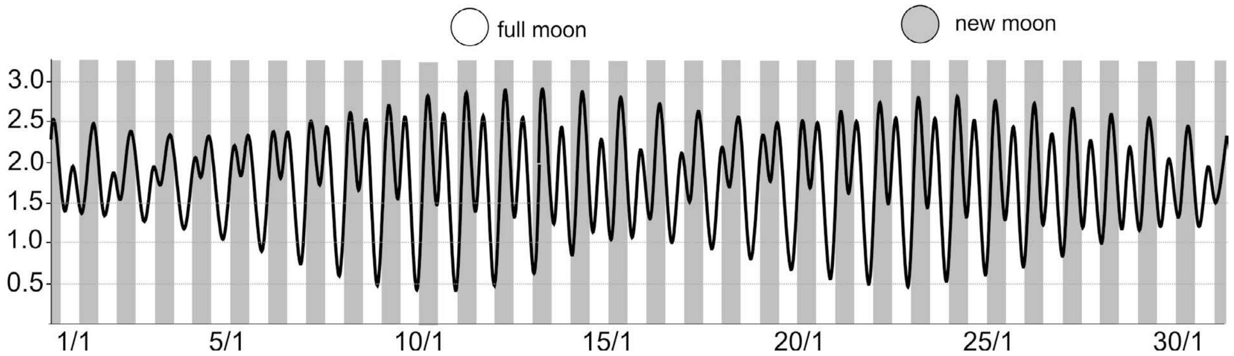

Figure 5.5. Complex tidal cycle of Barr Al Hikman (tidal station at Hilf, predicted tidal heights above Lowest Astronomical Tide (LAT); http://www.ukho.gov.uk/Easytide/easytide/).

Scale of importance

Intertidal mudflats and sabkhas are fed with sediment and nutrients by wind-blown deposits (Chapter 4) and receive sediments and nutrients from the sea (Chapter 3). Presumably, hydrodynamic conditions are heavily affected by conditions offshore.

Conclusions and Research Questions

Understanding landscape morphology and hydrodynamics is crucial for a thorough understanding of the Barr Al Hikman ecosystem. Fine scale information about bathymetry, currents and waves is currently lacking. A basic hydrodynamic model to simulate flooding, currents, waves, and transport at the intertidal flats of Barr Al Hikman would be useful in order to study these phenomena in detail. Therefore we propose:

- To map the spatial and temporal distribution of morphological variables. Probably multispectral imaging can be used for mapping of sediment characteristics;
- To investigate the possibility to set up and run a hydrodynamic model for Barr Al Hikman to simulate the hydrodynamic conditions;
- To investigate the technical possibilities to improve the bathymetry and to model flooding and drying of intertidal flats. Bathymetries can be constructed by means of multibeam in the subtidal and with UAS in the intertidal;
- To examine temporal variation in geomorphology and hydrodynamics;
- To examine interaction between landscape morphology, hydrodynamics and primary and secondary consumers.

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Part II: Food web dynamics

6 – Primary productivity

Katja (C.J.M.) Philippart

Introduction

Coastal marine ecosystems, including intertidal systems where parts of the seafloor are emerged during low tide, belong to the most productive systems of the world. If primary productivity is an indication of the carrying capacity for higher trophic levels, then highly productive coastal systems can serve as breeding, nesting, overwintering and migration stop-over grounds for large numbers of birds and as nursery grounds for large fish stocks (e.g. Pauly and Christensen 1995, Cloern et al. 2014). Large inputs of nutrients and organic carbon from land and oceans support high rates of primary production of pelagic microalgae in the shallow waters. Within estuaries and other shallow coastal marine areas, total aquatic primary productivity is not only determined by phytoplankton, but also by non-phytoplankton microalgae (e.g. microphytobenthos, epiphytes), submersed and floating vegetation (e.g. seagrass), marsh vascular plants (e.g. mangroves) and riparian vegetation (Robinson et al. 2016).

Knowns

Primary production budget
For all primary production groups, the annual production (ton C yr^{-1}) within Barr Al Hikman was estimated based on a multiplication of area-specific annual production (gC m^{-2} yr^{-1}) and area (km^2). Calculations of primary producer groups situated in the intertidal were based upon a total area of the mudflats of 190 km^2 (Fouw et al. 2017). For subtidal phytoplankton and seagrass productions, calculations were based upon a total area of 95 km^2 assuming that (i) Barr Al Hikman extends to the offshore borders of the adjacent subtidal seagrass beds, (ii) subtidal seagrass can be found up to a depth of 2-3 m (Jupp et al. 1996), and (iii) the area 0-2m depth was 50% of that of the intertidal (webapp.navionics.com/#boating/).

Phytoplankton
This production was derived from satellite estimates, assuming that the PP in the coastal subtropical Barr Al Hikman was similar to that of the larger-scale Exclusive Economic Zone "Oman" (www.seaaroundus.org). After assuming that pelagic production can only take place when the tidal flats are emerged (on average, half of the time), the production of the intertidal (190km²; 50%) and subtidal (95 km²; 100%) area would add up to more than 90.000 tons carbon per year (Table 6.1).

Seagrasses
A large part of the intertidal mudflats is covered by seagrass meadows containing the seagrasses *Halodule uninervis* and *Halophila ovalis*. The seagrass *Thalassia hemprichii* is found in particular in the subtidal area (Jupp et al. 1996; Bom et al. in prep.). The tidal flats of Barr Al Hikman are distributed over three subareas that have different densities of seagrasses, being Ghubbat Hashish bay area (52 km², low densities of seagrass), East coast (88 km²; partly covered with dense seagrass beds) and Khawr Barr Al Hikman (49 km²; no seagrass beds) (de Fouw et al. 2017). Assuming that the average coverage by seagrass of the first two intertidal areas is 50%, then Barr Al Hikman contains ((88+52)/2 =) 70 km² intertidal seagrass beds. Assuming a similar distribution of seagrass in the subtidal as in the intertidal, the total cover of seagrass in these deeper waters would be (70/190 * 95 =) 35 km². Based upon an average productivity of 2.7 gDW m^{-2} (Duarte and Chiscano, 1999) and a carbon content of seagrass dry weight of 35% (Fourqurean et al. 2012), the annual seagrass production of the intertidal and subtidal areas at Barr Al Hikman would add up to more than 36.000 tons carbon per year (Table 1). Here it is assumed that the average productivity is seagrass is that without the contribution of epiphytes.

Epiphytes
These microalgae attached to seagrass leaves may contribute strongly to overall productivity of coastal systems. While in some areas epiphytes accounted for 26% to 50% of seagrass productivity (Kitting et al. 1984), other areas report a contribution of three times the productivity of the seagrasses themselves (Moncreiff et al. 1992). Assuming that at Barr Al Hikman, the productivity of the epiphytes is more or less comparable to that of the intertidal seagrass, this would then be more the 24.000 tons carbon per year (Table 6.1).

Microphytobenthos
Assuming that all areas that are not covered by seagrass beds (190-70=) 120 km²) are inhabited by benthic algae with an average productivity of 0.13 gDW m^{-2} (Duarte and Chiscano 1999) and with a carbon content of 19% DW for diatoms (Sicko Goad et al. 1984), than the annual production by microphytobenthos at Barr Al Hikman would add up to more than 24.000 tons carbon per year (Table 6.1).

Mangroves
Based upon the total area of mangroves at Mahout and Mahout Island (Fouda and Al-Muharrami, 1995) and the productivity of *Avicennia marina* (Day et al. (1996), the annual production of the mangroves within Barr Al Hikman would add up to 2000 tons carbon per year.

Total
Based upon scattered information, the total primary production of the Barr Al Hikman area (subtidal and intertidal, including mangroves) would add up to more than 165.000 tons g C yr^{-1}, with phytoplankton and the seagrass-epiphyte communities being the main contributors (Table 1). These findings are in concordance with several other studies on productivity of seagrass-dominated ecosystems in the US where phytoplankton production contributed 47% to 72% to the system's production (Moncreiif et al. 1992).

Phytoplankton dynamics
With regard to seasonal and long-term variation the productivity in the various groups of primary producers, most is known on phytoplankton dynamics (although mostly at an ocean-basin wide scale). Satellite data show two climatological phytoplankton blooms in this region,

Producer group	Area km²	Productivity gC m^{-2} yr^{-1}	Production Tonnes C yr^{-1}	%
Phytoplankton	190	485	92.150	56%
Microphytobenthos	120	90	1.080	7%
Epiphytes	70	345	24.150	15%
Seagrasses	105	345	36.225	22%
Mangroves	5	400	2.000	1%
			165.325	**100%**

Table 6.1. Rough (!) estimates of primary productivity in Barr Al Hikman as derived from various sources. See text for data sources and calculations.

a wintertime bloom peaking in February and a summertime bloom peaking in September (Sedigh Marvasti et al. 2016). During the winter monsoon, winds shift from southwesterly to northeasterly, stirring up currents that bring up nutrients from the depths and out from coastal tributaries. The change in wind direction also picks up dust from the arid lands of southwestern Asia, a different source area than during the summer season, when dust is delivered to the ocean from the Arabian peninsula (Chapter 4). Mineral dust contains a lot of nutrients that phytoplankton need to fuel their growth (Banerjee and Kumar 2014).

Under specific conditions red tide phenomena tend to develop along the Omani coast (Fig 6.1). Red tide is a phenomenon caused by algal blooms during which the colour of coastal waters changes. Specifically, a couple of species of dinoflagellates are responsible for the red colour of the phenomenon. Red tides tend to occur when nutrient concentrations in the water column are high (Richlen et al. 2010) in combination with high amounts of oxygen-deficient water near the sea's surface (do Rosário Gomes et al. 2014) resulting in an increase in the frequency of fish kill incidents (Harrison et al. 2017). This may occur under natural conditions due to upwelling of nutrients but blooms can also be stimulated by nutrient loading from human activities such as agriculture. Algal blooms may result in depletion of oxygen and the release of toxins causing fish to die and illness in humans and other animals.

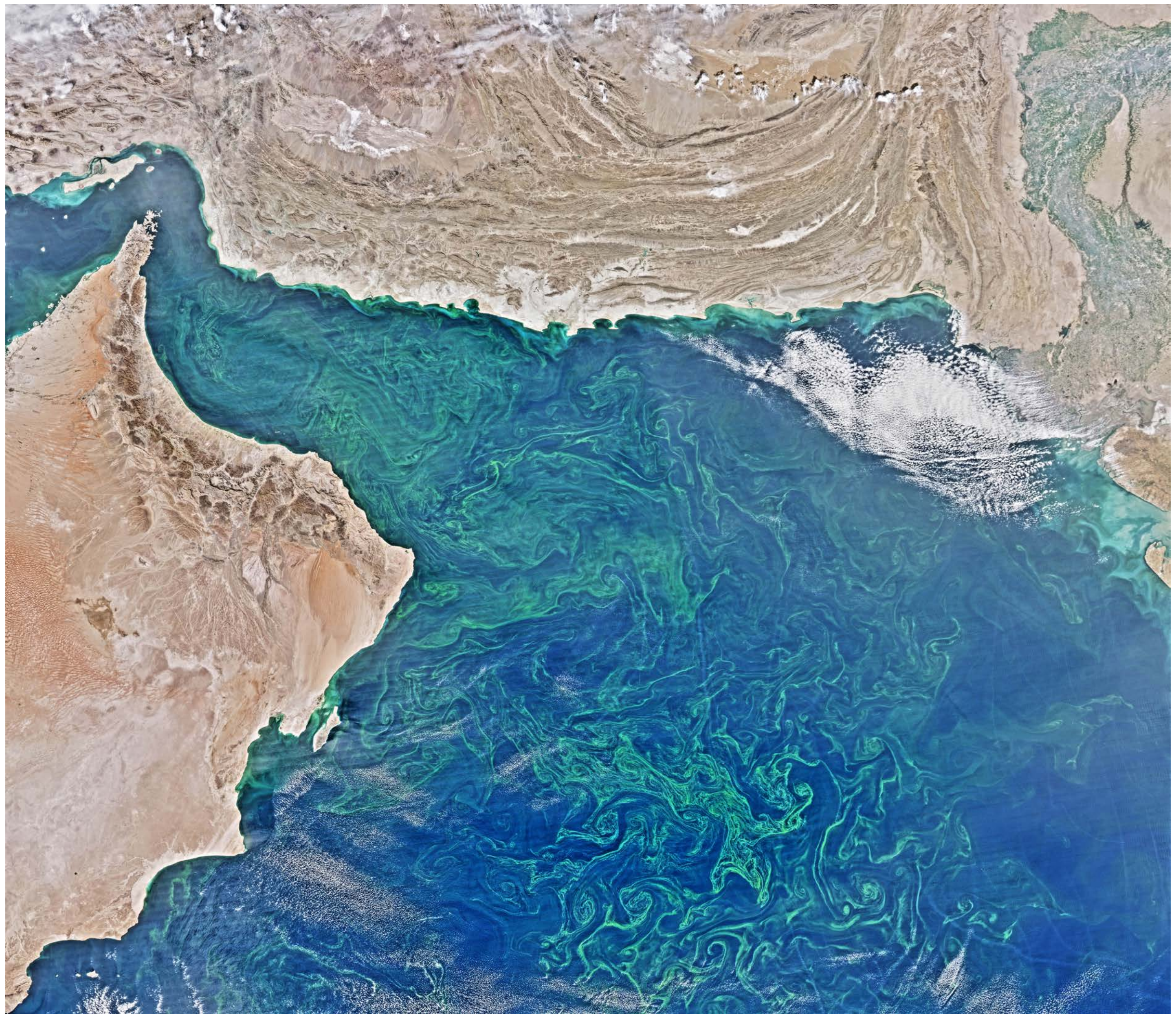

Figure 6.1. Satellite image showing phytoplankton blooms of Oman (left) on December 21, 2015 (http://earthobservatory.nasa.gov).

Table 6.2. Estimates of primary productivity of phytoplankton in subtropical and tropical EEZs, that include internationally important intertidal mudflats larger than 5000 ha (Fedde 2000), as determined by estimated from Earth Observation (www.seaaroundus.org)

EEZ	Intertidal Mudflat Systems	mgC m^{-2} d^{-1}
Mauritania	Banc d'Arguin	2.454
Nambia	Sandwich Harbour; Walvis Bay	1.542
Oman	Barr Al Hikman	1.327
India	Gulf of Khambhat; Gulf of Kachh	948
Suriname	Bigi Pan, Coppenamemonding, Wia Wia	868
Gulf of Thailand	Gulf of Thailand; Pattani Bay	759
China	Bohai Bay	724
Mozambique	Between Save and Buzi River	618
Australia	Roebuck Bay; Bowling Green Bay; Eighty-mile Beach; Shoalwater & Corio Bays	515
Viet Nam	Xuan Thuy Natural Wetland Reserve	419

In both the Arabian Gulf and the Gulf of Oman, there is evidence that red tides and their impacts are increasing (Richlen et al. 2010; do Rosário Gomes et al. 2014). In the past, fish ate the copepods that fed on the plentiful diatoms. But in the inter-monsoon season of spring 2015, the plankton was community dominated by *Noctiluca scintillans* (the green mixotrophic form; Harrison et al. 2011), which may have acted as seed stock for the summer bloom trigged by the mixing and subsequent injection of nutrients into the upper layer, induced by the summer (southwest) monsoon (Piontkovski et al. 2017). In contrast to the diatoms, *Noctiluca scintillans* appears to be too large for consumption by copepods but is fed on by species such as jellyfish and salps. Red tides may have large impacts on the marine ecosystem but is also of concern for the tourism and fishery industry. How exactly this disruption to the traditional food chain will impact regional fisheries remains to be seen (do Rosário Gomes et al. 2014).

Unknowns

Variation in time and space of production of primary producers in Barr Al Hikman remains unknown. We lack knowledge on how primary production transfers to higher trophic levels. Furthermore, the consequences of the apparent increase of *Noctiluca* blooms on pelagic primary production, foodweb and carrying capacity of Barr Al Hikman for birds and fish are not known.

Scale of importance

Compared to other Exclusive Economic Zones (EEZs) that include large (> 5000 ha) intertidal mudflats of international importance, the EEZ that contains Barr Al Hikman belongs to the most productive areas in the world (Table 2). If primary productivity is an indication of the carrying capacity for higher trophic levels, then Barr Al Hikman is very attractive as breeding, nesting, overwintering and migration stop-over grounds for birds and as a nursery ground for many fish species.

Conclusions and Research Questions

A first estimation of primary productivity indicates that Barr Al Hikman belongs to the most productive coastal areas in the world. The effectiveness of conservation management, such as safeguarding species and habitats, is hampered by the lack of systematic documentation of historical and present day productivity and trophic transfer. In other words, a baseline is missing.

- The major scientific questions are (i) how and why the productivity of this coastal marine ecosystem differs in time and space and (ii) how sensitive the local assemblages and their productivity are to local and global developments such as climate change, fisheries, habitat destruction and pollution (including eutrophication).

- In addition, information is needed on the quantity, quality and timing of the primary production in order to determine the consequences for the rest of the food web.

- More quantitative information on the variation in productivity, on the chain of events following human activities affecting coastal marine ecosystems and on the expected efficiency of conservation measures is a prerequisite for sustainable management of this rich, valuable and variable environment.

- It is, therefore, proposed to develop a mechanistic primary productivity model, and validate this model using Earth Observations and in situ measurements. The spatial and temporal resolution should be high enough to incorporate relevant habitats for and seasonality in productivity of various productivity groups, their drivers and the fate of the organic matter produced (including trophic transfer within the food web).

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7 – Primary consumers: Benthos community

7 – Primary consumers: Benthos community

Roeland A. Bom

Introduction

Primary consumers of intertidal areas transform primary production in food items that can be harvested by (in)vertebrate predators that move in at high tide (fish) and low tide (birds) (Herman et al. 1999; Fig 7.1). Important primary consumers in intertidal ecosystems are benthic invertebrates (all organisms that live on or below the sediment surface), for example bivalves, gastropods, polychaetes and crustaceans. Thus, characterizations of the food-webs of intertidal mudflats usually begin with assessments of the composition of the (standing stock) benthic community (Honkoop et al. 2006; Honkoop et al. 2008; Piersma et al. 1993), which can further be interpreted spatially, for instance in relation with environmental variables (Compton et al., 2013), or consumers of macrozoobenthos (Zwarts, 1988; Zwarts et al. 1990), or temporally in relation to human activities including eutrophication and fisheries (Beukema, 1991; Kraan et al. 2010). Predators can deplete a benthic community within a year (Zwarts et al. 1990), hence knowing benthic production rates (turnover) is essential for a better understanding of how standing stock densities are maintained.

Figure 7.1. Benthic organisms are an essential food resource for shorebirds. Here a lesser sandplover *Charadrius mongolus* with a polychaete (image by J. van de Kam)

Knowns

Macrozoobenthic invertebrates (all benthos > 1mm) are the most noticeable benthic organisms of Barr Al Hikman and the main food for avian and marine predators (Bom et al. 2017). Field observations show that the benthic community of Barr Al Hikman has a high biodiversity. This is probably a typical feature of marine ecosystems in the Indo-West Pacific (IWP) (Renema et al. 2008). A more quantitative picture of the benthic community was obtained from a sampling campaign in January 2008 and in the winters of 2011-2015 (Bom et al. 2017). Until now, 97 benthic species are identified, mainly gastropods, bivalves and brachyuran crabs (Bom et al. 2017 and Bom et al. in prep). Standing stock densities in January 2008 were 20 gram ash-free dry mass (AFDM)/m^2 and numerical densities amounted to 1770 individuals/m^2. These standing stock densities are in the same order of magnitude compared to other intertidal mudflat areas (Dittmann, 2002; Piersma et al. 1993; Fig 7.2). Samples collected in January 2008 further showed that almost all the benthic biomass consisted of gastropods (67%) and bivalves (23%). Crustaceans (6%), and polychaetes (4%) contributed less to the biomass densities. Three species (the gastropods *Pirenella arabica* and *Cerithium scabridum* and the bivalve *Pillucina fischeriana*) made up 78% of the biomass density. Samples collected over the period 2011-2015 showed that crab densities can fluctuate a factor 4 between winters. Field observations showed that molluscs are an important resource for marine predators (crabs and fishes), whereas the avian community mainly feeds on crustaceans and polychaetes (Bom et al. 2017).

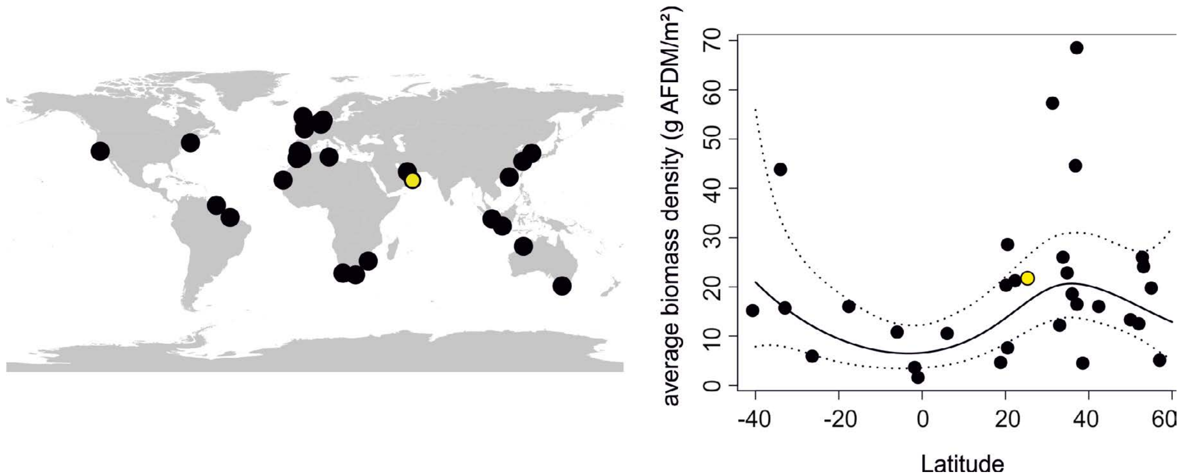

Figure 7.2. Intertidal mudflats are rare but productive habitats. The left figure shows a world map with some of world's larger intertidal systems with Barr Al Hikman in yellow. The right figure plots the average biomass density per site against latitude, with Barr Al Hikman in yellow. Biomass density tends to be lower at the equator and peaks at intermediate latitudes. The biomass density found in Barr Al Hikman fits well in this picture (after Piersma et al. 1993)

Unknowns

Many of the less-abundant benthic species remain unidentified. Except for some of the crabs (Bom et al. in prep), virtually nothing is known about the year-to-year variation of the benthic community and also the causes of the annual fluctuations in the benthic community remain unknown (e.g. temperature, predation, upwelling system). Likewise, production estimates (turnover) of the primary consumers remain unknown. Furthermore, it is unknown how benthic invertebrates contribute to the functioning of the ecosystem. For instance, the very abundant *Pirenella* and *Cerithium* gastropods may be essential in nutrient recycling whereas bivalves may be essential for the maintenance of seagrass beds (van der Heide et al. 2012). For several of the avian predators and all the marine predators it remains unknown which benthic species are used as a resource.

Scale of importance

Most benthic species are entirely resident to the area after larval settlement. Many benthic species have a pelagic phase early in their development, but this probably does not extend far from the mudflats. Shrimps use the intertidal area as a nursery ground (Mohan and Siddeek, 1996) (see box I).

Conclusions and Research Questions

Benthic invertebrates are essential to the functioning of the intertidal ecosystem. Yet, our knowledge on the benthos is incomplete. For a deeper understanding of the intertidal food web it is necessary to study the benthic community more thoroughly by means of monitoring, field observations and experiments. This includes:

- A yearly sampling scheme to monitor annual variation in standing stock densities (Fig 7.3);
- A monthly sampling program to understand how standing stock densities are maintained and affected by seasonality;
- Estimate consumption rates by avian and marine predators;
- Estimate production rates to understand how the benthic standing stock densities are maintained;
- Experiments to understand how the benthic community contribute to the functioning of the intertidal ecosystem.

Figure 7.3. Most benthic species remain hidden under the ground. To study them, a core and a sieve is all you need. (image by J. van de Kam)

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8 – Higher trophic levels: Fish

Henk W. van der Veer & Kees (C.J.) Camphuysen

Introduction

Worldwide coastal ecosystems are characterized by high productivity, not only primary production but also secondary and tertiary production (Ketchum, 1983). An important component of primary and secondary consumers is formed by pelagic and demersal fish communities. Fish communities are an important component in the functioning of these ecosystems which in turn act as important nursery grounds for a variety of fish species (van der Veer et al. 2001) (Fig 8.1). Coastal nursery areas are defined and characterized by a concentration of juvenile fish, whereby the advantage for a species in adopting a shallow coastal nursery area seems to be the potential for increased growth due to relatively higher water temperatures in combination with the escape from most predators. Depending on the life cycle characteristics of a species, nursery areas can cover a variety of habitats from sandy bottoms, sea grass meadows, mangroves and coral reefs. Furthermore, fish communities of coastal systems are also an important food source for a variety of bird species. Barr Al Hikman, with an area of about 190 km^2 of intertidal mudflats, is such a nursery area. Based on our own observations and on the local catches of various rays and shark species, the Barr Al Hikman ecosystem can be considered as relatively pristine with still a high biodiversity (Al-Jufaili et al. 2010). This may contrast with many other coastal areas that are prone to overfishing (Halpern et al. 2008; van der Veer et al. 2015).

Knowns

Qualitative information about the fish fauna of Oman including Barr Al Hikman is available in the from Randell's (1996) guide on the coastal fish community of Oman. Based on general descriptions a raw list of species potentially occurring species at Barr Al Hikman can be composed. Various species have been collected for stable isotope analysis (de Fouw et al., 2017; unpubl) during expeditions at Barr Al Hikman over the last decades. The most recent updated list is presented in Table 8.1. So far, about 40 species have been found of which 32 species were positively identified. Another sources of information are local fish landings of (Fig 8.2). The variety of shark and ray species caught in shallow waters particularly indicated that this areas supports rich and relatively pristine fish fauna with overall a low and small scale coastal fishing intensity. Also the presence of high numbers of fish-eating birds in the area such as grey herons western reef-egrets, great cormorants, and various gull species (de Fouw et al., 2017; unpubl.), indicates that fish biomass and hence production must be substantial.

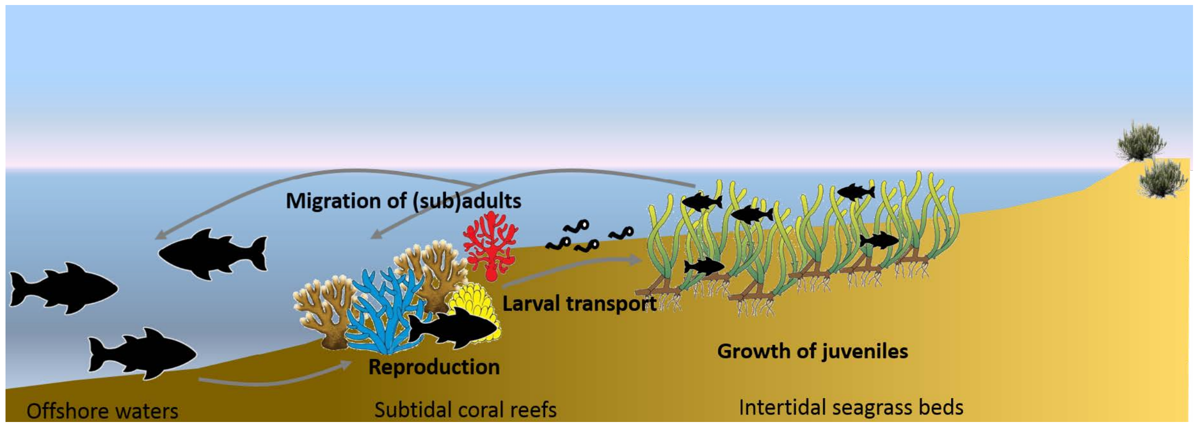

Figure 8.1. Example how coastal systems function as fish nursery and are interconnected.

Table 8.1. Most abundant fish species caught and identified during various expeditions at Bar Al Hikman (de Fouw et al., 2017; unpubl).

Latin name	English name
Ablennes hians	flat needle fish
Acanthopagrus omanensis	blackmargined seabream
Alepes djedaba	shrimp scad
Aphanius dispar	arabian killifish
Atherina pinguis	silverside
Gerres longirostrus	strongspine silver-biddy
Glaucostegus halavi	halavi guitarfish
Hemiramphus marginatus	black-edge halfbeak
Lutjanus decussatus	checkered snapper
Lutjanus lineolatus	lined snapper
Lutjanus quiquelineatus	fivelined snapper
Moolgarda cunnesius	wedgesnout mullet
Palutrus meteori	meteor goby
Platax orbicularis	circular platax
Platycephalus indicus	Indian flathead
Sardinella longiceps	Indian oil sarine
Terapon jarbua	jarbua terapon
Terapon puta	small-scaled terapon
Tomiyamichthys latruncularius	fan shrimp-goby
Triacanthus biaculeatus	short-nosed tripodfish

Fisheries

The Sultanate of Oman's fishery is for national use as well as for export to countries such as Jordan and landlocked African countries. The prime target species are tuna, sardine, large jacks, mackerel, sailfish, barracuda, snappers, groupers, sea breams, sharks, rays, shrimp, lobster, cuttlefish, and abalone. Fishing gear used includes purse seines, beach seines, hand lines, gill nets, trolls, long line and traps. Key landing ports are Bukha, Khasab, Kumzar, Lima and Dibba (Musandam Governorate), Shinas, Sohar, Saham, Al Suwaiq and Al Khabourah (Al Batinah North Governorate), As Seeb and Quryat (Muscat Governorate), Sur, Al Ashkhara and Masirah (Al Sharqiah South Governorate), Al Lakbi (Al Westa Governorate), Mirbat, Salalah and Dhalkoot (Dhofar Governorate). Omani form the majority of fishermen deploying small boats (Σ ~18,000 boats). Indian and Bangladeshi use dhows (Σ ~700 vessels), while most industrial boats have Korean, Chinese, Indonesian, Philippine, or Vietnamese crews and owners (Σ ~110 vessels). Small fiberglass boats operate up to 6 NM - Artisanal boats fish beyond 6 NM - Coastal fleet operate beyond 8 NM - Industrial boats operate beyond 10 NM - Fishing patterns in the artisanal sector depend on the targeted species mainly. Large pelagics are targeted in the early morning, as do fish species caught in demersal trap fishing. Small pelagic are targeted after sun rise. In the evening fishermen use drift gill nets for fishing. This pattern may differ between different governorates [Ministry of Agriculture and Fisheries, Sultanate of Oman 2013].

Unknowns

Quantitative information about the distribution, abundance, biomass of the fish community is lacking for both demersal and pelagic species. No systematic inventory of the area has been made so far. Therefore, no production data are available and also the role and importance of

Figure 8.2 Local fish catches at Shannah near Barr Al Hikman (images by J. van de Kam (above) and H. van der Veer (below))

the fish fauna in the food web is unknown. Furthermore, it is unknown for which species Barr Al Hikman acts as a nursery area and if so during which life stages. This also implies that the spatial scale at which the Barr Al Hikman nursery supplies juveniles to offshore adult stocks is unknown. Although fishing in the area is done with small boats and their individual impact might be small their impact in total can be large but it is currently unknown whether it is sustainable.

Scale of importance

In line with migration patterns of fishes in other coastal nurseries, the spatial scale will be substantial (hundreds to thousands km). However the absolute scale of importance is unknown and more research is needed.

Conclusions and Research Questions

Basic information about the food web structure of the fish community at Barr Al Hikman is still far from complete. No quantitative data, including data on productivity of the various pelagic and demersal species is available. Anecdotic data indicates the Barr Al Hikman area still represents a relatively pristine intertidal area with most likely an important nursery function for various fish species. The importance of the fish community as food source for migrating birds is unknown, but bird data suggests that it might be substantial. No quantitative information is present about the fishing pressure in the Barr Al Hikman area, but it cannot be ruled out that it is increasing.

For insight in the fish productivity in Barr Al Hikman and the importance of the area as a nursey and fuelling station, collection of quantitative information is a prerequisite, including:

- A yearly sampling scheme to monitor annual variation in standing stock densities;
- A monthly sampling program to understand how standing stock densities are maintained and affected by seasonality;
- Estimate consumption rates by avian and marine predators;
- Estimate production rates to understand how the fish stocks are maintained;
- Quantification of the spatial and temporal patterns in fishing pressure;
- Quantification of the scale of importance of Barr Al Hikman as a nursery area for offshore fish stocks.
- Experiments to understand how the fish community contributes to the functioning of the intertidal ecosystem.

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BOX I
Nursery grounds

Roeland A. Bom & Jimmy de Fouw

Intertidal ecosystems like Barr Al Hikman often have a crucial function as nursery ground for a number of marine species. These species may have an enormous ecological and economical value, and include crustaceans (shrimps, lobsters and crabs) and fish species (Levin et al 2001; van der Veer et al 2001; Zijlstra 1972). The advantage for a species to adopt a shallow coastal nursery area seems to be the potential for increased growth due to relatively higher water temperatures in combination with the escape from most predators.

Barr Al Hikman has been recognized as such a nursery ground for a number of species. The role of the area as a nursery ground for Indian white shrimp, *Penaeus indicus* was recognized two decades ago (Mohan and Siddeek, 1996) but needs to be updated. More recent observations show that the area also serves as an important nursery ground for blue swimming crabs *Portunus segnis* (Bom et al submitted; Fig B1.1) reaching densities that are unprecedented in the word. Both species are important resource for species higher up in the food web (this report) and blue swimming crabs are among the most beneficial resource for commercial fisheries in the area (MAFW 2014). Based on our observations that the intertidal zones around the Barr Al Hikman peninsula are teeming with small fish, it is most likely that the area serves as a nursery ground for many more species. This remains to be investigated.

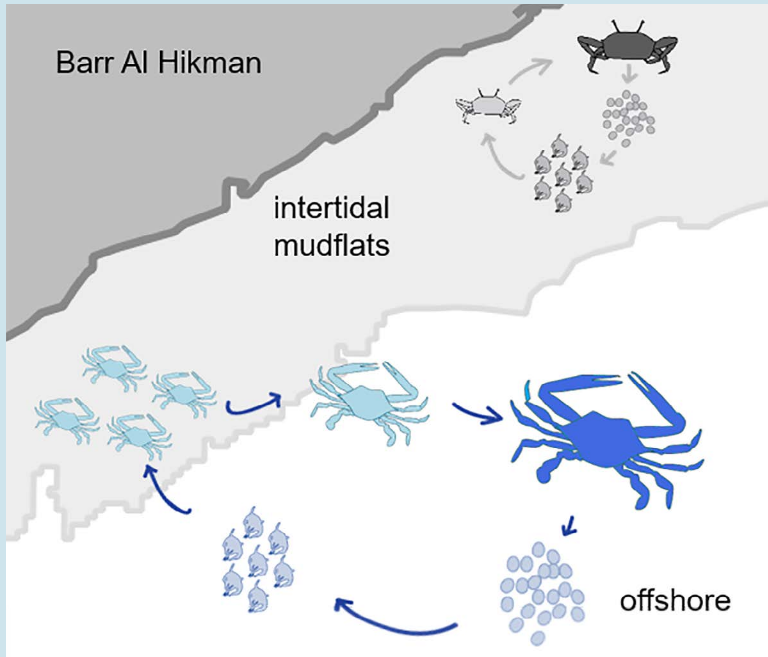

Figure B1.1. From Bom et al. submitted. Proposed life cycle of crabs in Barr Al Hikman. Blue swimming crab use the intertidal area as a nursery ground. Small crabs grow up in the area. Larger crabs move to the sublittoral where they spawn. Megalopae (postlarvae crabs) move to the intertidal area. Other crabs may be entirely connected to the intertidal area.

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9 – Higher trophic levels: Benthic feeding wading birds

9 – Higher trophic levels: Benthic feeding wading birds

Jimmy de Fouw

Introduction

Worldwide shorebirds are the most visible animals of coastal wetlands. During low tide they can be found on the mudflats in search of food and at high tide they cluster together in large groups waiting for the next feeding opportunity when the tide drops again. Barr Al Hikman is one of the most important wintering- and stopover sites for migratory shorebirds in the Middle-East. These shorebirds originate from breeding grounds stretching all the way from Scandinavia to eastern Siberia (Fig 9.1). In Barr Al Hikman, these world travellers mingle with local breeders. Birds wintering further south use the site to make migratory stopovers, both during spring and autumn, in order to replenish their exhausted energy reserves. Without a 'stepping stone' in the Middle East these birds cannot complete their migrations between their high-arctic breeding grounds and southern wintering areas. Loss of the mudflats of Barr Al Hikman would be disastrous for many populations of migratory birds.

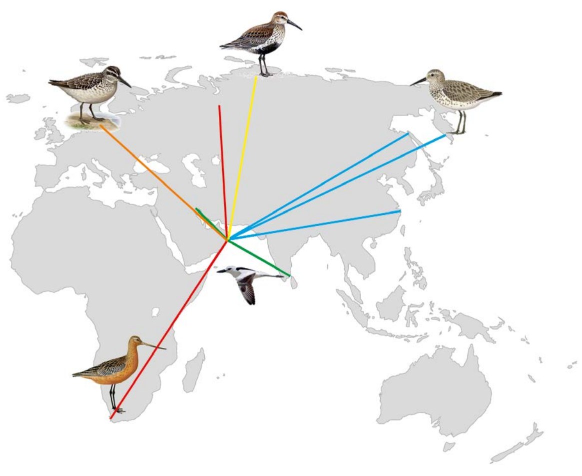


Figure 9.1. Resigthings of ringed birds and their connection with Barr Al Hikman, Borad-billed sandpiper, Dunlin, Great knot, Crabplover and Bar tailed Godwit (from left to right, top to below).

Knowns

Barr Al Hikman is an important wintering site for migratory waterbirds in the Asian-East African Flyway. A systematic survey of the area was conducted in 1990 and more recently in three winters between 2008 and 2016. As many as half a million waterbirds of 42 species were counted. Shorebirds were by far the most numerous species group (> 410,000)(de Fouw et al. 2017). For 18 species of shorebirds, the population wintering at Barr Al Hikman exceeded more than 1% of their flyway population (Table 9.1) (de Fouw et al. 2017), the threshold that is used to designate an area as a Ramsar site. These counts show that Barr Al Hikman is among the most important wintering grounds for shorebirds in the Middle-East and the Asia-East African Flyways, both with respect to the number of birds and in terms of species diversity. Ringing and tagging studies shows that Barr Al Hikman links wetlands on a global scale (Fig 9.2). Compared to numbers from the past shows, it appears that numbers of shorebirds tripled since the nineties (Fig 9.3). All mudflats of Barr Al Hikman are important feeding grounds. Large numbers of birds roost along the coast at the high tide line. However, a large proportion roosts inland on the sabkha during high tide.

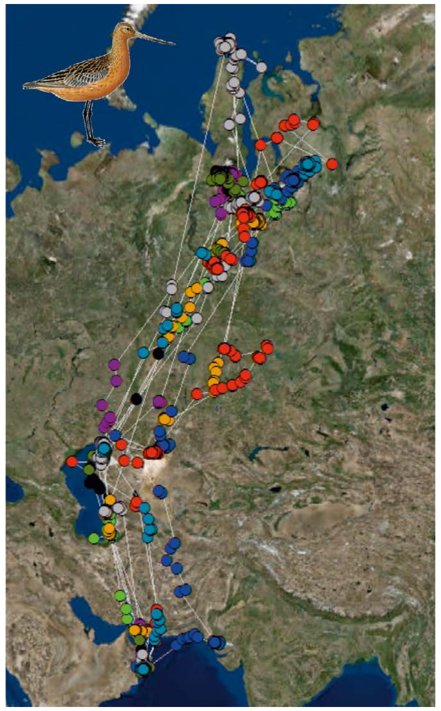
Unknowns

Surveys confirm the importance of the site for waterbirds during winter. Barr Al Hikman is presumably also important for the shorebirds that winter further south, for example in east and southeast Africa. These birds might use the site to make migratory stopovers, both during spring and autumn, in order to replenish their exhausted energy reserves. Without a 'stepping stone' in the Middle East these birds can most probably not complete their migrations between their high-arctic breeding grounds and southern wintering areas. However, there is a big gap in the knowledge about how many migratory shorebirds that winter in Africa, make use of stopover sites in the Middle East, both in spring and autumn (Delany et al. 2009). A rough estimate is that every year at least one million migratory (shore)birds use Barr Al Hikman, either to spend the winter or for a migratory stopovers in spring/autumn. It is however fairly unknown to what extent the birds that winter in Africa indeed stop in the Middle East in autumn and in spring. To obtain information about the number and diversity of birds that uses Barr Al Hikman during the spring, and to learn about the seasonal dynamics in bird numbers at this site, we recommend that complete surveys are conducted during several months throughout the year. If the Middle East is indeed an important stopover site for migratory birds

Table 9.1. Number of shorebird species wintering at Barr Al Hikman that exceed the 1% threshold of the estimated flyway population (based on max count of 2008, 2013 and 2016).

species	flyway population estimation	year max	% flyway population
crab plover *Dromas ardeola*	600,000–80,000	2013	11–15%
oystercatcher *Haematopus ostralegus*	27,000–40,0001	2013	14–20%
Kentish Plover *Charadrius alexandrinus*	25,000–100,000	2008	1–8%
lesser sandplover *Charadrius mongolus*	100,000–125,000	2016	>100%
greater sandplover *Charadrius leschenaultii*	25,000–100,000	2016	15–60%
grey plover *Pluvialis squatarola*	90,000	2013	5%
turnstone *Arenaria interpres*	100,000	2016	7%
sanderling *Calidris alba*	150,000	2016	2%
great knot *Calidris tenuirostris*	2,000–5,000	–	24–60%2
curlew sandpiper *Calidris ferruginea*	400,000	2008	9%
dunlin *Calidris alpina*	500,000	2013	26%
little stint *Calidris minuta*	1,000,000	2013	2%
broad-billed sandpiper *Limicola falcinellus*	61,000–64,000	–	8%3
Eurasian curlew *Numenius arquata*	25,000–10,000	2016	15–58%
bar-tailed godwit *Limosa lapponica*	100,000–150,000	2013	58–65%
redshank *Tringa totanus*	100,000–1,000,000	2013	4–37%
greenshank *Tringa nebularia*	100,000–1,000,000	2013	0–2%
terek sandpiper *Xenus cinereus*	100,000–1,000,000	2013	0–2%

1) Roomen et al (2015); 2) Green et al (1994), Evans (1994), 3) Eriksen (1996)



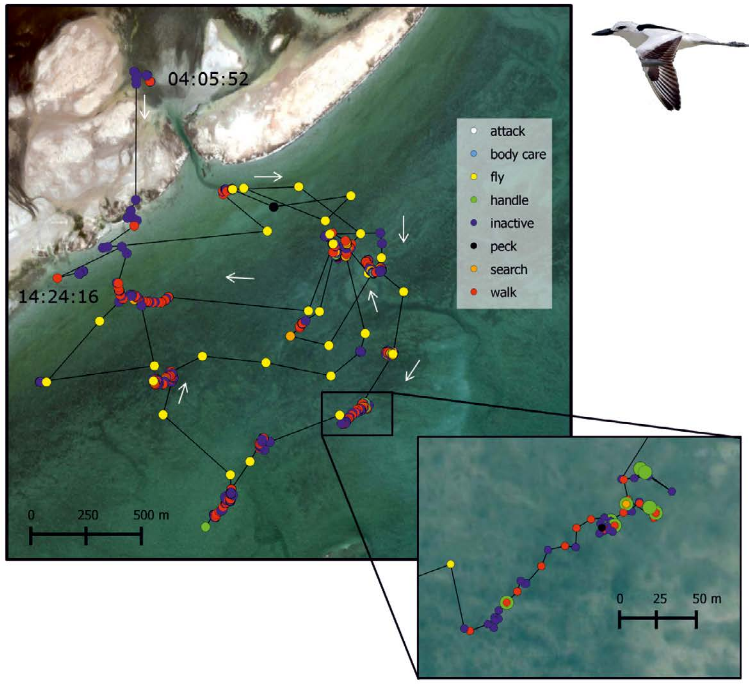


figure 9.2 a). Migration of nine bar-tailed godwit in 2015 measured with Argos PTT trackers.
b) Movements of a crab plover carrying a GPS logger and an accelerometer during a single low tide on 20 November 2012. The acceleration data was used to classify the behaviour (Bom et al. 2014). The time between points is, in general, 30 seconds. After each measured position, acceleration was measured during 10 seconds.

from Africa in spring we expect that very many birds are staging in the area in April.

Furthermore, surveys show that shorebirds tripled since the nineties, yet the cause of the increase of bird numbers remains unknown. The spatial use of feeding and roosting shorebirds has been poorly studied. For instance, which sites are the most important for feeding or roosting and how is the sabkha used as roosting site across the circadian and tidal rhythms. The picture of the migratory connectivity between sites is far from complete. The firsts steps have been made with tracking of bar tailed godwits and crab plovers.

Scale of importance

The scale of importance stretches from local (e.g. crab plovers, kentish plover) to about 10,000 km distance (e.g. great knot, bar tailed godwit) along the Asian-East African Flyway. Migratory birds typically travel thousands of kilometres between (sub)arctic breeding grounds and wintering areas that are often found near or even south of the equator. Often migration distances are too large to be covered in one single flight. In such case a chain of suitable sites (wetlands) is required to enable the travelling birds to reach their favourable wintering areas. Different migratory flyways are recognized which represent different chains of sites (van de Kam et al. 2004; Delany et al. 2009). Loss of a wetland implies that the flyway has one link less

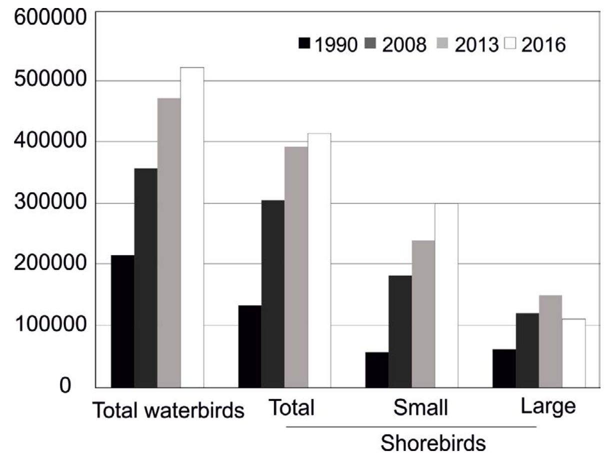


Figure 9.3. Bird numbers of systematic surveys since the nineties. Birds counts in 1990 adapted from Green et al. (1994).

in its series, and it will thus be more difficult for a migratory bird to complete its annual migrations. Therefore, migratory connectivity depicts the links that migrant birds make across the globe and can have important consequences on individuals, populations and communities. Barr Al Hikman is an important link within the flyway and its influence stretches on a global scale.

Conclusions and Research Questions

Our surveys confirmed that Barr Al Hikman is the single most important wetland for wintering birds in the Middle East, not only with respect to the number of birds, but also in terms of species diversity (Delany et al. 2009). Therefore Oman, and particularly Barr Al Hikman, has recorded a higher diversity of wader species in internationally important numbers than any other area within Africa and Western Eurasia. The Asian – East African migratory flyway system is still poorly understood. Even basic information like the size of the flyway populations of different bird species is lacking. Moreover, we have no idea about temporal trends. Clearly, knowledge of long-term population trends is needed. Therefore it is important to

- Develop a monitoring plan: Annual monitoring and several moments throughout the year;
- Colour ring several focal species (bar-tailed godwits, crab plovers, great knots) to identify their migration routes and to monitor their demography (Bom et al. 2018; Piersma et al. 2016);
- Study how the birds use the site, by focal observations and tracking of shorebirds.

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BOX II
Arms races

Roeland A. Bom

The macrozoobenthic community of Barr Al Hikman is dominated by molluscs (Chapter 7), yet molluscivorous shorebirds are almost absent from the area (Chapter 9). A study by Bom et al. (2018) showed that the near absence of molluscivorous shorebirds extends to all shores along the Indo-West Pacific (IWP), while many of these shores are dominated by molluscs as well. On almost all other intertidal areas in the world, where densities of molluscs are similarly high as in Barr Al Hikman, molluscivorous shorebirds are abundant winter visitors, notably the red knot, *Calidrus canutus* (Fig B2.1).

Fig B2.1. Bom et al. (2017) shows that the molluscan community of Barr Al Hikman has extremely well developed anti-predation traits and are therefore unavailable to shorebirds. Most molluscs were unavailable either because of their hard-to-crush shells, or because they lived too deeply in the sediment. Repair scars and direct observations showed that molluscs are subject to crab predation (Fig B2.2). This fits with earlier observations of Vermeij (1977a, 1977b, 1989) that molluscan prey in the IWP evolved strong anti-predation traits in a prolonged evolutionary arms race with durophagous predators including brachyuran crabs. Bom et al.(2017) concludes that the established strong molluscan anti-predation traits against crabs precludes molluscan exploitation by shorebirds at Barr Al Hikman. The study illustrates that evolutionary arms races can have consequences for the global distribution of species.

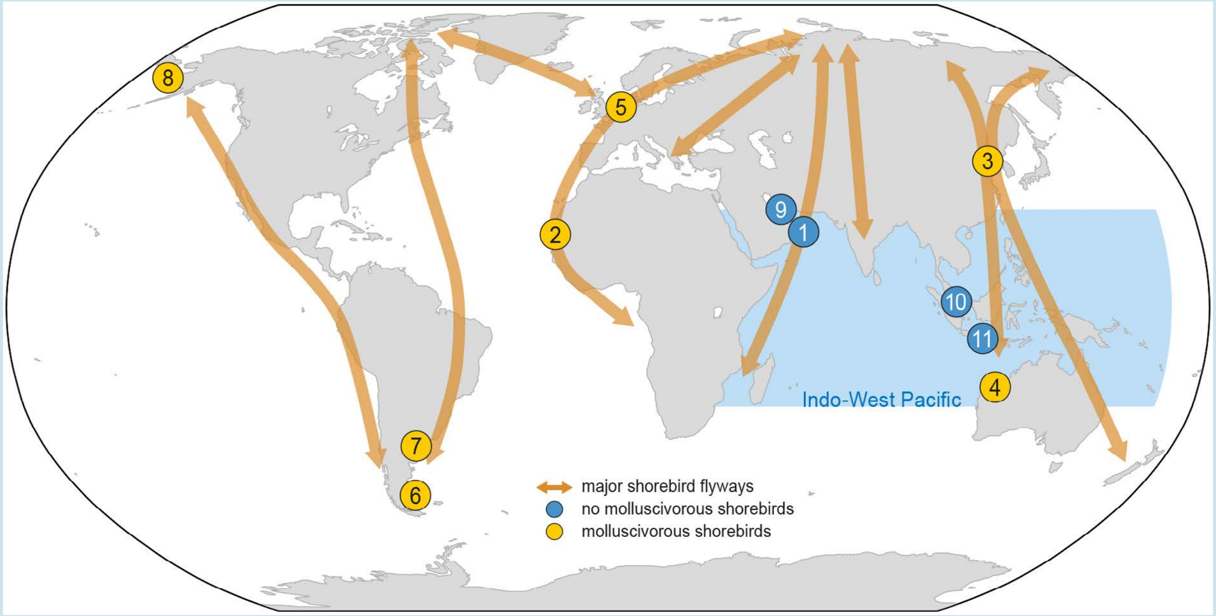

figure B2.1

figure B2.2 (images by J. de Fouw (above) and M. Ebbinge (below)

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10 – Higher trophic levels: Piscivorous coastal birds

10 – Higher trophic levels: piscivorous coastal birds

Kees (C.J.) Camphuysen

Introduction

The intertidal zones around the Barr Al Hikman peninsula are teeming with fish and several species of these (may) use the area as a nursery ground (Chapter 8, Box I). Not only does the area around Barr Al Hikman sustain a considerable commercial fishing industry, but also a large number of avian piscivorous birds for which the area is of international significance (de Fouw et al. 2017). Fish eating birds that utilise these waters in large numbers include various heron species (most of which as semi-residents to the area), great cormorants *Phalacrocorax carbo*, Eurasian spoonbills *Platalea leucorodia*, some waders, gulls, terns and one fish-eating raptor (mostly passage migrants or wintering species). Exactly what fish species are taken and which of these species form the so-called staple diets of the main predators is largely unknown. The numbers of some of these fish eating birds are so large, however, that a better understanding of their foraging requirements and feeding strategies is urgently required to facilitate effective conservation measures for Barr Al Hikman in future years. With developing fisheries in waters around the peninsula but also in the area itself, it should be better understood where the benefits for birds (discards) and the overlapping demands for birds and humans (prey fish for birds that is also commercially fished) are situated in this system.

Foraging strategies

Piscivorous wading birds such as waders, herons and egrets and other nearshore waterbirds including terns and gulls use a variety of foraging techniques including slow stalking, sit-and-wait, active pursuit, and aerial foraging at the surface, such as dipping or aerial plunges (Frederick 2002; Camphuysen and Garthe 2004). Many species are diurnal feeders, but some forage most frequently nocturnally. Many species forage during crepuscular hours at both ends of the day, in some cases despite weather and tidal conditions.

Piscivorous birds[1] often feed in dense mixed-species flocks with other waterbirds (Fig 10.1). In Barr Al Hikman in Oman, for example, feeding frenzies of western reef herons *Egretta gularis* together with slender-billed Gulls *Larus genei* are frequently observed (illustrated above). The pros and cons of flock feeding versus solitary feeding are not always fully understood. Large aggregations are a mix of conflicting pressures for individuals trying to reap the benefits (dense prey, increased foraging success, decreased patch search time, increased overall vigilance for and safety from predators) and avoid the costs (increased attraction of predators, competition for prey, dominance interactions, interruption of foraging bouts, theft of prey items) of social foraging. Master et al. (1993) suggested that snowy egrets *Egretta thula* in the USA were obligate in their use of dense foraging aggregations, because their active foraging behaviours were, for a variety of reasons, most efficient in those situations, but the feeding success of individual birds may decrease with flock size. Territorial feeders tend to forage solitarily by stalking, a strategy that is hindered by the activity of other individuals nearby. Although multi-specific feeding associations (MSFAs) are a conspicuous and frequent feature of wading bird (and seabird) foraging behaviour, solitary and territorial feeding also is typical for many species. Many taxa switch between these two tactics. Wiggins (1991) found that there were significant energetic costs to egrets defending individual feeding territories, but that solitary birds tended to catch larger fish than did flock-foraging egrets. In multi-species feeding flocks, the intake rates of individual birds (joiners, scroungers, kleptoparasites) may be higher as a result of involuntary facilitation by other species (divers, producers) foraging on the same prey (Camphuysen and Webb 1999).

[1]This chapter deals with "piscivorous" birds, but many species regularly switch between small fish and small crustaceans as prey.

Knowns

The results of three systematic surveys of the whole Barr Al Hikman peninsula conducted in the winters 2007/2008, 2013/2014 and 2015/2016 showed that over 20, at least partially piscivorous waterbirds occurred in numbers within the area (Table 10.1; De Fouw et al. 2017). Foraging areas and prey choice are overlapping between these species, but their foraging tactics and prey size vary such that inter-specific competition is reduced. Whether and when flock feeding or solitary feeding may be more profitable for each of these species, or under which conditions this may change, is open for detailed investigations.

Figure 10.1.Feeding frenzy of western reef herons and slender-billed gulls, Barr Al Hikman, 25 Feb 2017, (image by CJ Camphuysen)

Unknowns

It is largely unknown which fish species are a resource for which of the piscivorous predators in the Barr Al Hikman ecosystem, therefore it is unclear what their role is in the Barr Al Hikman food web (Chapter 8).
A central problem in documenting the costs and benefits of flocking in piscivorous waterbirds has been to separate the effects of quality of foraging site from the effects generated by the fact of many birds foraging together (competition or social facilitation). Costs and benefits may also be related to (unknown) year-to-year variation of the fish community.

Scale of importance

Most herons are semi-resident to the area, Slender-billed Gulls and various waders are passage migrants and or wintering species.

Conclusions and Research Questions

The Barr Al Hikman intertidal area is teeming with small fish, including small pelagics as well as juvenile forms of reef fish and other taxa. Multi-species feeding associations (MSFAs) are often observed within the intertidal gullies in Barr Al Hikman, comprising mostly herons and spoonbills accompanied by small gulls and with small tern species foraging in the periphery of the frenzies. For a deeper understanding of the intertidal food web it is a prerequisite to study the multi-species foraging associations and compare the costs and benefits with individual foraging tactics (including territoriality) by means of monitoring, field observations and perhaps experiments:

- Assessments of diets from partly digested prey remains for all piscivorous predators
- Observations to assess the frequency of MSFA formation (relations with tide, day light and prey abundance)

Tabel 10.1. Feeding methods, tendency to feed in flocks and preferred prey size in commoner piscivorous species in the Barr Al Hikman intertidal area in Oman. Prey size: small = <4cm, medium = 4-10cm, large is <10cm in fish length.

Species	**Feeding method**	**Interaction feeding**	**Fish size**
great cormorant *Phalacrocorax carbo*	Swimming, foot-propelled pursuit diving	In (large) flocks or solitary	Large
Eurasian spoonbill *Platalea leucorodia*	Wading,	Small groups or solitary	Medium
grey heron *Ardea cinerea*	Wading, stalking	Solitary or small concentrations	Large
great egret *Egrettta alba*	Wading, stalking	Solitary or small concentrations	Large
little egret *Egrettta garzetta*	Wading, stalking	Solitary or small concentrations	Medium
western reef heron *Egretta gularis*	Wading, stalking	Mostly in flocks, also solitary	Medium
spotted redshank *Tringa erythropus*	Wading, hit-and-run	Solitary	Small
greenshank *Tringa nebularia*	Wading, hit-and-run	Solitary	Small
slender-billed gull *Larus genei*	Aerial search, shallow plunge diving, dipping	Flocks	Small-medium
great black-headed gull *Ichthyaetus ichthyaetus*	Aerial search, shallow plunge diving	Small flocks	Medium-large
sooty gull *Larus hemprichii*	Aerial search, shallow plunge diving	Flocks	Medium-large
large white-headed gull *Larus fuscus/cachinnans/barabensis/heuglini*	Aerial search, shallow plunge diving	Flocks	Medium-large
gull-billed tern *Gelochelidon nilotica*	Aerial search, shallow plunge diving	Solitary or small flocks	Medium
Caspian tern *Sterna caspia*	Aerial search, deep plunge diving	Solitary	Medium-large
swift tern *Sterna bergii*	Aerial search, deep plunge diving	Small flocks	Medium
lesser crested tern *Sterna bengalensis*	Aerial search, deep plunge diving	Small flocks	Medium
sandwich tern *Sterna sandvicensis*	Aerial search, deep plunge diving	Small flocks	Medium
saunders's tern *Sterna saundersi*	Aerial search, shallow plunge diving	Solitary or small flocks	Small-medium
white-winged black tern *Chlidonias leucopterus*	aerial search, dipping	Small flocks	Small
common tern *Sterna hirundo*	aerial search, shallow plunge diving, dipping	Solitary or small flocks	Small-medium
osprey *Pandion haliaetus*	aerial search, shallow plunge diving	Strictly solitary	Large

- Near-shore feeding frenzies still require more attention, but MSFAs include associations of (resident) Indo-Pacific humpback dolphins *Sousa chinensis* and (wintering) Pallas's Gulls *Ichthyaethus ichthyaethus*.
- A sampling program to assess species and size composition of prey fish (complementary with Chapter 8)
- Estimate consumption rates (intake rates) of flock feeders versus solitary feeders

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11 – Higher trophic levels: Sea turtles

11 – Higher trophic levels: Sea turtles

Kiki (E.M.) Dethmers

Introduction

Green (*Chelonia mydas*), Hawksbill (*Eretmochelys imbricata*), Loggerhead (*Caretta caretta*) and Olive ridley sea turtles (*Lepidochelys olivacea*) use beaches and shallow coastal regions of Oman for nesting and foraging. Oman is considered a globally important area for populations of three of these four threatened species of sea turtles. Loggerhead and Hawksbill turtles nest on Masirah Island at densities rarely observed elsewhere in the world and it is believed that the Loggerhead population of this island is the largest globally. This is unusual because Loggerhead turtles generally prefer temperate regions for nesting, while Hawksbill turtles are generally found to nest at higher latitudes (e.g. Butt et al. 2016).
Loggerhead turtles fitted with satellite transmitters were shown to extensively use pelagic habitats in addition to coastal neritic ones during the post-nesting phase, with the largest individuals mostly utilising the oceanic realm. The shallow region between the island and the mainland saltmarsh of Barr Al Hikman is a known foraging hotspot for Hawksbill as well as green turtles (Salm et al. 1993; Rees et al. 2010; Rees et al. 2012; Pilcher et al. 2014; Fig 11.1).
While nesting activity and success on Masirah island and post-nesting migration has been relatively well studied, the importance of the foraging area remains relatively poorly understood. Highly productive coastal marine ecosystems (see Chapter 6), have the potential to support a broad diversity of secondary consumers such as sea turtles. The four turtle species that utilize Barr Al Hikman and off-shore waters each have specialized foraging strategies and diets; hawksbills prefer sponges and algae, loggerheads feed principally on gastropod and bivalve molluscs, and hermit crabs, green turtles eat sea grass, and olive ridleys feed on gastropod molluscs and small crabs.
This highly productive area also attracts an increasing level of fishing pressure (see Chapter 8) . There is little doubt that this will have a considerable impact on non-targeted species such as sea turtles. With increasing temperatures and rising sea levels also putting pressure on the persistence sea turtles, an in-depth study Barr Al Hikman as a potential globally important sea turtle foraging area is strongly encouraged from a conservation perspective.

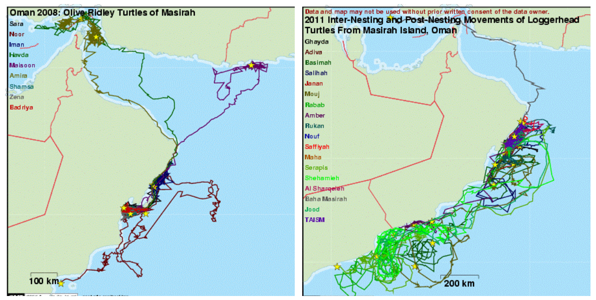

Figure 11.1. Satellite tracks of Olive Ridley Turtles and Loggerhead Turtles from Oman.
Images from SEATURTLE.ORG Maptool. 2002.

Knowns

Turtle Species nesting in Oman
Hawksbill – several 10.000 turtles / year on Masirah Island
Loggerhead – several 10.000 turtles / year on Masirah Island
Green – 5.000 turtles / year
Olive ridley – 150 turtles / year

Turtle foraging hotspots in Oman
Hawksbill turtles from the Daymaniyat islands in Northern Oman use foraging sites off southern-end of the Barr Al Hikman peninsula as do hawksbill turtles from Masirah. Home ranges of the Oman hawksbill turtles were substantially smaller than those from the nearby Arabian Gulf, which has been suggested to explain why Oman hawksbill turtles are larger in size than their neighbours. Barr Al Hikman is believed to be key foraging habitat for this species (Pilcher et al. 2014).

Turtle mortality
Anthropogenic mortality of turtles has been reported since at least two-and-a-half decades ago. Weideplan (1991) reports "many turtles" killed along the Barr Al Hikman mainland and Masirah beaches. Between 1984 and 1992 the IUCN carried out a seven-year study of the entire coast of the Sultanate of Oman with one of the main objectives to determine and map distributions of coastal and marine resources and activities (Salm et al. 1993). The authors mention fishery-related threats, which include harvest of eggs and turtles, and accidental drowning in trawl, drift and gill nets, blocking of nesting beaches by gill nets, and trapping of hatchlings in gill nets spread over beaches for maintenance. Harvesting for food and accidental drowning of turtles in trawl and drift nets reached massive and unsustainable levels in the Gulf of Masirah. For example, 19 dead hawksbill turtles were found along the tide line of southern Barr Al Hikman during their nesting season in 1990. Another 10 green, eight loggerhead, and five olive ridley turtles were found along this 30 kilometre stretch of coast. In March 1991, 118 dead turtles were observed along 250 kilometres of the Barr Al Hikman coast (Salm et al. 1993).

Since those earlier reports, human induced mortality of turtles continues to occur with one recorded incidence of over 50 green turtles killed in June 2014 (Mathilda via facebook pers. comm.). However, no targeted surveys have been carried out to quantify the severity of this type of mortality in relation to e.g. natural mortality in the region. Nor is it clear if human induced mortality has caused a decline in turtles population of Oman.

Unknowns

Several intensive tagging programs have elucidated some of the migratory pathways of adult female turtles of at least three of the four species that occur in the coastal waters of Oman. However, there is no information about the movement and habitat-use by adult male and juvenile turtles. The main drivers of the Barr Al Hikman coastal ecosystem for attracting sea turtles remain unidentified. Which are the main source of mortality and what is the effect of current mortality rates on local populations? The sustainability of fisheries-related turtle mortality along the coast of Oman has not been investigated. Is the Oman coastal system a stronghold for the endangered Hawksbill and Loggerhead turtles and vulnerable Green turtles in the Indo-Pacific region and/or globally?

Scale of importance

The coastal area of Barr Al Hikman is believed to be a key foraging habitat for hawksbill and possibly also for green turtles in the Gulf region. There are very few other places in the world where such large numbers of hawksbills have been observed and given that the Indo-Pacific hawksbill population is declining at an alarming rate, it possible that the Barr Al Hikman area is of regional, if not global importance to prevent a total collapse. With the world's largest population of loggerhead turtles nesting on Masirah Island, located just off-shore from Barr Al Hikman, it is imaginable that Barr Al Hikman is utilised by loggerhead turtles during their interesting periods.

Table 11.1. Observed turtles at Barr Al Hikman (see associated Fig 11.3)

Date	Loca-tion	Species	CCL (cm)	CCW (cm)	Tail (p-t)	Tain (c-t)	Sex	DNA	Comments	Possible cause of death	Photo ID
22-02-2017	BaH river	Cm	91.5	-	-	-	?	BaH1	Plastron removed / butchered	Hunting / By-catch	1
22-02-2017	BaH river	Cm	78.5	-	-	-	?	-	Carapace split	By-catch / Boatstrike	2
24-02-2017	BaH camp	Cm	49.5	-	-	-	?	BaH2		By-catch / Drowning	3a, 3b
24-02-2017	Shannah	Cm	99.9	-	-	-	F	S1	Bloated but not rotted	By-catch / Drowning	4a, 4b
24-02-2017	Shannah	Cm	92.6	-	43	29.3	M	S2	Concave plastron, full of commencals	By-catch / Starvation	5a, 5b
24-02-2017	Shannah	Cm	105	-	-	-	F	S3	Carapace split	By-catch / Boatstrike	6
24-02-2017	BaH camp	Cm	81.2	70.2	-	-	?	BaH3	Decomposed	By-catch / Drowning	7
24-02-2017	BaH camp	Cm	86.2	71.5	40	-	M	BaH4	Large hole in L ventral scute	By-catch / Drowning	8a, 8b

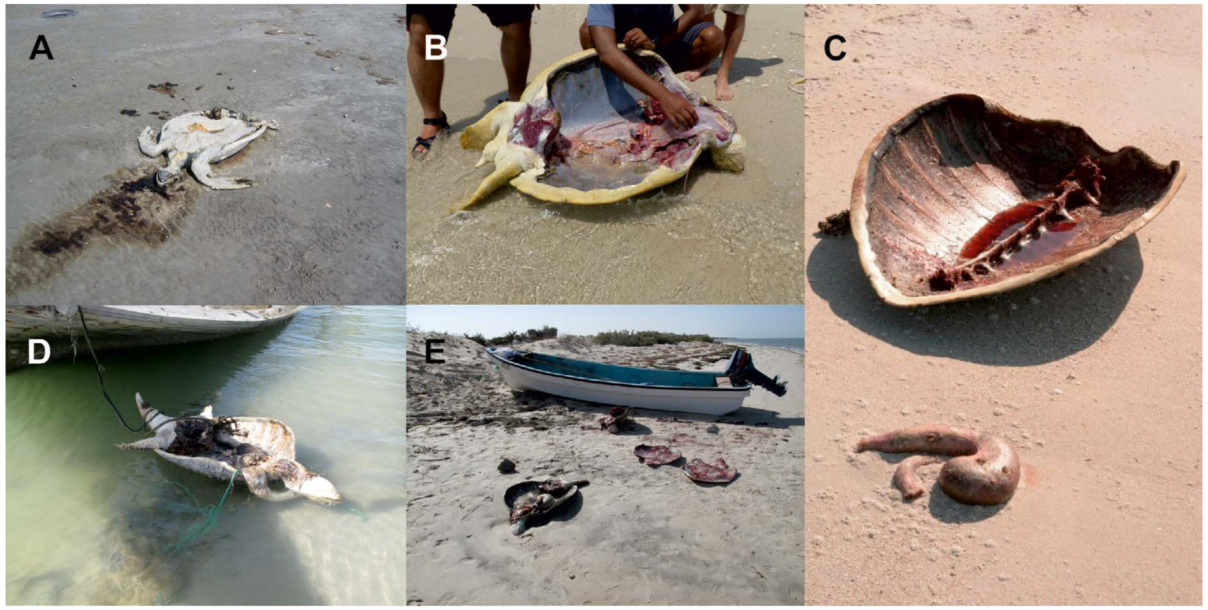

Figure 11.2. Some examples of turtle takes, observed during the expeditions between 2007-2017. A) Filim (2007), B, C) Shannah at island Ma'awil (2014, 2017), D) fishing village and on E) beach at the bay of Ghubat Hashish (2013). (picture credits: B Mathilda on Facebook, C Aziza Saud Al-Adhubi)

Observations

During a 3-day survey at Barr Al Hikman in late February 2017, we observed a dozen turtles. All were dead and at various stages of decay. Of those, eight were positively identified as green turtles based on carapace scute patterns (Table 11.1). There was no evidence of any other species at that time of the year. Size class ranged from 49.5 to 105 cm CCL (Curved Carapace Length) and two were adult males, based on the size of the tail. All animals had recently washed up on shore and died at sea. There were 2 cases where the turtle had evidently been slaughtered, one had its plastron removed, the other had possibly been speared. All other animals had clearly drowned, possibly as a result of entanglement in a fishing net from which they had subsequently been cut out. There was one case (ID 5), where the animal had a concave carapace, dense algal growth on the carapace and dense growth of commensals on the plastron. This is usually a sign of a sick and starving animal. Skin samples were collected for future DNA analysis and stored at the Sultan Qaboos University in Muscat.
In addition, we also observed several remains of turtles on the sabkha, sometimes at a distance of several hundred meters away from the high water mark. Presumably these were animals that had come up with spring tide and were caught out on the receding tide, stranded on the salt marsh, and subsequently succumbed to the heat.

During a survey across Ma'awil, a pile a turtle bones provided evidence that poaching of turtles does occur in the area and during scientific expeditions the last decade poaching was yearly observed (Fig 11.2).

Conclusions and Research Questions

- There is evidence for several causes of mortality including drowning through interaction with fishing gear, direct harvesting, disease, starvation, and probably 'inexperience';
- The majority of mortalities during this survey involved adult reproductive green turtles;
- It is interesting to note that no loggerhead or hawksbill turtles were observed during survey. This is possibly related to nesting seasonality, which does not start until late April. Furthermore, much of the fishing activities at Barr Al Hikman occurs in the shallow areas where green turtle feed on the sea grass;
- Future studies would need to focus on the spatial and temporal variation of movement patterns of 4 sea turtle species, their differential use of the coastal ecosystem and relationship to local biophysical processes;
- Post mortem and stomach contents analyses could identify if disease and/or starvation are important causes of mortality in Barr Al Hikman.

Fig 11.3. (Images by K. Dethmers (1-6) and by R.Bom (7–8b))

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12 – Higher trophic levels: Offshore seabirds and marine mammals

12 – Higher trophic levels: offshore seabirds and marine mammals

Kees (C.J.) Camphuysen

Introduction

The geography of the offshore waters of Oman, i.e. the Gulf of Oman and the Arabian Basin (Kerstein et al. 2000) or Arabian Sea (International Hydrographic Bureau 1953), its oceanographic properties, and the fisheries activities in that area all suggest that the Arabian basin, one of the most productive and dynamic marine areas on earth, is of great importance for seabirds and marine mammals. This includes the deeper parts of the Arabian Sea, but especially the shelf break, the shallow shelf, and the nearshore waters connecting to, for example the Barr Al Hikman area.

As a result of the Somali Current upwelling (Chapter 3), internationally important foraging areas and feeding aggregations of apex predators may be expected with a seasonally changing species composition, including residents (local breeding seabirds and non-migratory cetaceans) and migrants from both Hemispheres. Unfortunately, the area is notoriously understudied in terms of at-sea distribution patterns, foraging opportunities, and overall (seasonal) abundance of charismatic megafauna such as seabirds, sea turtles, and marine mammals (Salm et al. 1993, OBIS Seamap 2017, http://seamap.env.duke.edu/). From a conservation point of view (status and abundance within the region, fisheries interactions, marine protected areas), as well as in a purely ecological context, but also given the risks for oil incidents within the area now that newly discovered offshore resources of hydrocarbons will be exploited in the foreseeable future, it would be important to investigate the offshore area in depth.

Knowns

Seabirds

Seventeen species of seabirds breed on the islands and coasts of southern Iran and the Arabian Peninsula, of which six species and four subspecies are endemic to this desert and trpical or sub-tropical region (Gallagher et al. 1984) (Table 12.1). In addition, numerous seabirds occur as passage migrants or as wintering seabirds, and this includes species from both Hemispheres, such as (Eriksen and Victor 2013) (Table 12.1).

Important seabird areas in Oman include the Musandam region (summer roosts of Socotra Cormorants), Umm al Fayyarin, Dayymaniyats, Fahal to Ra's al Hadd, Masirah, Kuria Muria group (Hasikiyah), Sawda, Hallaniyah, Gharzant, and Qibliyah (Gallagher et al. 1984).

Three breeding seasons have to be referred to, where the start of a season is marked by egg-laying. Summer breeders are species that lay in late May – July (mostly terns); winter breeders, including Socotra Cormorant, initiate clutches from the autumn onwards (October) but these species may nest in "waves", over a protracted period. Spring breeders lay their eggs between February and late April and include Caspian Tern, Saunder's Tern plus various herons and spoonbills. Some species, such as the Brown Booby, have been found nesting in most months of the year.

Marine mammals

Small boat surveys were conducted between 2000 and 2003 in three main regions of Oman's coastal waters: Muscat, the Gulf of Masirah and Dhofar to assess relative abundances of cetaceans. In order of frequency, these were (Minton et al. 2010):

Table 12.1 Seabirds of Oman

Seabirds	Local link
jouanin's petrel *Bulweria fallax*	regional breeding
Persian shearwater *Puffinus [lherminieri] persicus*	regional breeding
red-billed tropicbird *Phaethon aethereus indicus*	regional breeding
masked booby Sula *dactylatra melanops*	regional breeding
brown booby Sula *leucogaster plotus*	regional breeding
Socotra cormorant *Phalacrocorax nigrogularis*	regional breeding
sooty gull *Larus hemprichii*	regional breeding
white-eyed gull *Larus leucophthalmus*	regional breeding
Caspian tern *Sterna caspia*	regional breeding
greater crested tern *Thalasseu bergii velox*	regional breeding
lesser crested tern *Thalasseus begalensis*	regional breeding
dougall's tern *Sterna dougallii*	regional breeding
white-cheeked tern *Sterna repressa*	regional breeding
bridled tern *Onychoprion anaethetus*	regional breeding
sooty tern *Onychoprion fuscata*	regional breeding
saunder's tern *Sternula saundersi*	regional breeding
brown noddy *Anous stolidus plumbeigularis*	regional breeding
wedge-tailed shearwater *Puffinus pacificus*	wintering/migrant
wilson's storm-petrel *Oceanties oceanicus*	wintering/migrant
swinhoe's storm-petrel *Oceanodroma monorhis*	wintering/migrant
red-necked phalarope *Phalaropus lobatus*	wintering/migrant
pallas's gulls *Ichthyaethus ichthyaethus*	wintering/migrant
Caspian gulls *Larus cachinnans*	wintering/migrant
heuglin's gulls *Larus fuscus heuglini*	wintering/migrant
sandwich terns *Thalasseus sandvicensis*	wintering/migrant
and six species of skuas *Stercorarius spp.*	wintering/migrant

bottlenose dolphins Tursiops sp.,
long-beaked common dolphin *Delphinus capensis*,
humpback whale *Megaptera novaeangliae*,
spinner dolphin *Stenella longirostris*,
Indo-Pacific humpback dolphin *Sousa chinensis*,
bryde's whales *Balaenoptera* sp. and
risso's dolphin *Grampus griseus*

Other species observed were false killer whale *Pseudorca crassidens*, blue whale *Balaenoptera musculus*, rough-toothed dolphin *Steno* *bredanensis* and various beaked whales *Mesoplodon* spp. The nearshore areas of the Gulf of Masirah, as well as the coastal waters of Dhofar, were identified as areas of concentration for the Arabian Sea's recently designated endangered subpopulation of (non-migratory) humpback whales, as well as for Indo-Pacific humpback dolphins.

Unknowns

Basic information of offshore distribution patterns, relative abundance, foraging habitats and multi-species species aggregations (notably foraging interactions) is lacking and so are predator prey relationships within the area and the importance of the various offshore zones for species that may congregate and roost in the Omanis shallow lagoon systems, intertidal areas and that breed onshore.

Scale of importance

Recent tracking studies (Van Bemmelen et al. 2015), but also a small body of old data (Bourne 1960, Bailey 1966, Bourne 1991ab) suggest that these waters are of considerable (international) importance. No systematic work on the oceanic ranges of seabirds or their ecology has previously been undertaken in the tropical Indian Ocean and within the Arabian basin. This is reflected in poor knowledge of most species which occur there. Current impacts to the environment include consequences that arise from the widespread use of gillnets (damage to turtle and cetacean populations and coral areas), overfishing of some high-value fish stocks, and industrial fishing that has led to conflicts with artisanal fishers and may have affected foraging conditions for seabirds (Wilson 2000).

Conclusions and Research Questions

There are numerous reasons to conduct ship-based multi-species megafauna surveys using a combination of strip- and line-transect techniques from nearshore waters and well over the deeper ocean basin beyond the shelf-break. A better understanding of the connectivity between the nearshore areas (such as breeding grounds and intertidal areas as the Barr Al Hikman peninsula) and the offshore zone is just one of them. The effect of the seasonal upwelling for resident seabirds, marine mammals, turtles, and for migratory species could be assessed if standard observation techniques (Tasker et al. 1984, Buckland and Turnock 1992, Camphuysen et al. 2004) would be used in combination with systematic observations of (foraging) behaviour (Camphuysen and Garthe 2004) and records of classified foraging associations (Camphuysen and Webb 1999). Other key issues of research include the determination of:

- Offshore distribution and numbers (at-sea densities);
- Foraging ecology, prime resources;
- Species interactions, foraging aggregations;
- Movement patterns (onshore-offshore and vice versa);
- Important marine areas;
- Spatial patterns in oil sensitivity (particularly relevant during spills).

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13 – Food web structure

13 – Food web structure

Jimmy de Fouw, Ibrahim Al Zakwani & Tjisse van der Heide.

Introduction

Although most large animals that live in the intertidal area consume other animals, they still indirectly depend on plants. In fact, many marine food webs largely depend on algae and seagrass (Vonk et al. 2008; Christianen et al. 2017). Benthic animals, which spend most of their life in or on the sediment, feed on algae and seagrass (Chapter 7) and are in turn an important food source for larger animals such as fish and birds. Therefore, benthic animals form an important link between plants and fish and birds. An ecosystem consists of a diverse assemblage of species that differ in form and function, resulting in complex food webs. Food webs are networks of species eating one another (called 'trophic interactions'), often depicted as a web of 'nodes' (the species) and links (the feeding relations). Primary producers are autotrophic, typically photosynthesizing species that form the bottom of the network, also called the lowest 'trophic level'. Primary consumers are depicted one trophic level higher, and form a vital intermediate trophic layer that transfers the energy fixed by the lowest trophic level upward to the higher trophic levels, including secondary consumers and tertiary consumers, respectively (Fig 13.1). Species that feed on multiple trophic levels are called omnivores.

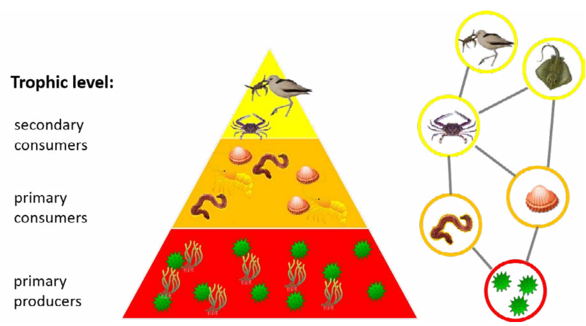

Fig 13.1 (A) Ecological (trophic) food web pyramid showing the relative biomass at each trophic level in a marine ecosystem. (B)

Knowns

In Barr Al Hikman, benthic and pelagic algae, together with seagrasses are the most important species groups consuming the lowest trophic level (see Chapter 6). The second trophic level (or primary consumers) largely consists of members from the benthic invertebrate community, including many bivalves, snails, and worms (see Chapter 7). Other species from this community, including many crustaceans such as crab and shrimp are omnivorous, which means that they can feed on multiple trophic levels. Finally, higher trophic levels are mostly made up of fish and waterbird species.

In November 2015, a comparison was made between seagrass beds and adjacent bare sites to show the relative importance of seagrass for the ecosystem (Fig 13.2). For this purpose, the ecological community of both habitat types was thoroughly sampled, and the trophic level of individual species determined using stable isotopes techniques. The results reveal that that there is a clear difference in food web complexity between two habitats (Fig 13.3). The seagrass food webs are typified by higher species richness, as well as a higher number of links compared to bare areas. This in turn yields a much more complex food web in seagrass beds compared to bare area, illustrating the importance of seagrasses for the functioning of the intertidal mudflats in Barr Al Hikman (Fig 13.3).

Figure 13.2. Study area at the east coast of Barr Al Hikman (left). Sampling and sorting benthic species from the mudflat (right). (images by J. van de Kam)

An intact, well-functioning local food web is vitally important for any of the species that are part of it. For instance, omnivorous intertidal crabs that are very abundant on the intertidal flats of Barr Al Hikman depend on both primary producers (seagrass, algae) and higher trophic levels (small crustaceans, worms, bivalves) to thrive. This intertidal habitat, however, does not function in isolation as a food web, but is linked to other habitats such as the landward situated sabkha's and mangrove stands, as well as the seaward located coral reefs and deeper pelagic zone. Clear examples of such spatial trophic links are (1) the transfer of detritus from seagrasses to the coral reefs by current and waves, and turtles, (2) the nursery function of seagrass beds for juvenile coral reef fish, and (3) bird migration between the sabkha's and seagrass beds (see Fig 13.4 for an in-depth explanation).

Unknowns

In many coastal ecosystems, habitat-forming foundation species such as seagrasses, mangroves and corals, play a pivotal ecosystem-structuring role (Stachowicz 2001, van der Heide et al. 2007). These species typically strongly alter the physical conditions of their environment (Jones et al. 1994) which is not only beneficial for the species involved but also for many associated species that live within the same ecosystem. The on-going food web studies are currently providing valuable new insights into the feeding relations and overall network structure of the Barr Al Hikman food web. Yet, it remains unknown how foundation species driven non-trophic interactions such as current and waves attenuation, sediment stabilization, and general habitat-provisioning affect the food web and general ecosystem functioning. Both trophic and non-trophic interactions act over various spatial scales (Van der Zee et al, 2012, Donadi et al, 2013, Christianen et al. 2017) and the Barr Al Hikman ecosystem harbours a

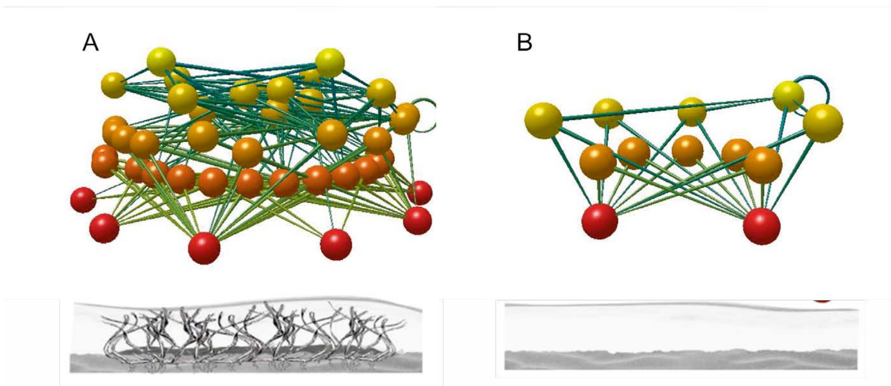

Figure 13.3. Food webs of (A) seagrass with fishes and (B) bare area. The food web of barren areas is typically simpler. Nodes represent species and lines represent links between species if a species is included in the diet of the species higher up in the food web. Node colours changes from red (basal species) to yellow with increasing trophic level.

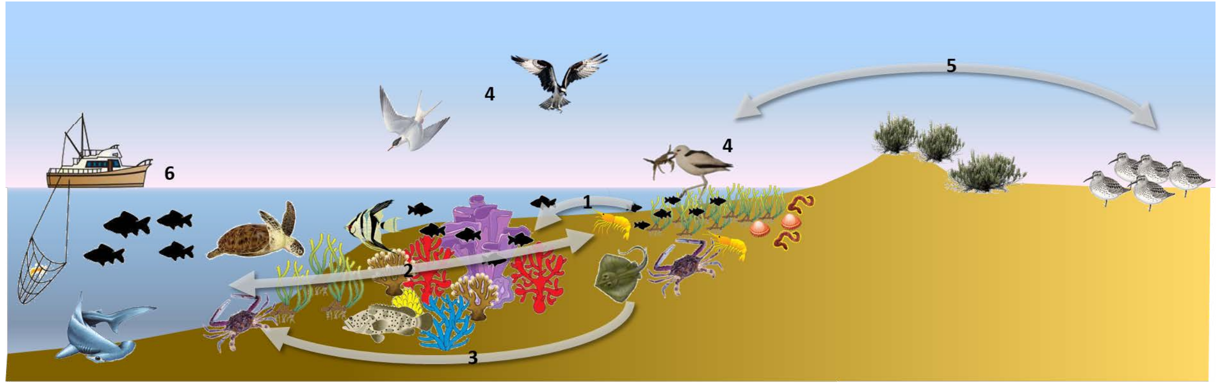

Figure 13.4. Examples of passive and active interactions between habitats. (1) Seagrass detritus feeds corals, (2) fish species use seagrass beds and corals as nursery area, (3) secondary consumers or predators (like swimming crabs and guitarfish) feed on shellfish/crustacean in seagrass beds and disperse between intertidal at high tide and offshore at low tide, (4) migratory birds (e.g. Crab plovers) forage on crabs, small fish and other benthic prey, (5) local movement of shorebirds between the sabkha's (roost) and intertidal mudflats (feeding), (6) economical important offshore fisheries depend on shallow coastal system like Barr Al Hikman (adapted from Heck et al. 2008).

variety of coastal foundation species, including seagrasses corals, mussel beds (Fig 13.5) and mangroves. We therefore argue that it is of utmost importance to further elucidate the ecological network of Barr Al Hikman in order to understand how its interactions control the functioning of this vital ecosystem.

Scale of importance

Ecological networks can be considered from the perspective of multiple interaction types and many spatial scales. On its simplest level

Figure 13.5. Locally, the bivalve *Pinna bicolor* can reach high densities, creating a habitat for other species. (image by J. van de Kam)

and at a very local scale, for instance, one can focus on the benthic food web inside a seagrass meadow. In contrast, one can also consider the large-scale ecological network of Barr Al Hikman as a whole, including trophic and non-trophic interactions within a habitat, and tropic and non-trophic links between habitats. The Barr Al Hikman system is characterized by a number of distinct but interconnected habitat types, including bare intertidal flats, seagrass meadows, coral reefs, mangrove stands and the pelagic zone. Recent studies have shown that cross-habitat interactions are of particular importance to coastal ecosystems such as Barr Al Hikman (Gillis et al. 2014; van de Koppel et al. 2015). We therefore argue that the functioning of the ecological networks of this system should be considered at a scale that encompassed all vital habitats.

Conclusions and Research Questions

To further elucidate the ecological network of Barr Al Hikman in order to understand how its interactions control the functioning of this vital ecosystem we recommend a sampling program to construct the food web relationships of the entire ecosystem, including the non-tropic relationships created by foundation species like seagrass beds, mussel beds, coral reefs. In addition, there are clear indications that Barr Al Hikman is an import part of an ecological network. The strong reciprocal dependency between habitats on a local and a global scale makes ecosystem connectivity a functional foundation of biodiversity, we therefore recommend to study this connectivity. Using stable isotopes techniques in combination with individual based tracking techniques makes it possible to determine to what their position is in the local food-web, what extend animal use each habitat on a local a global scale.

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14 – Conclusions and Research Questions

14 – Conclusions and Research Questions

Current knowledge assembled in this report indicates that Barr Al Hikman is a relatively pristine ecosystem that is extremely rich for its ecological and socio-economical values. The area ranks among the most pristine and productive coastal ecosystems on the planet, with microscopic benthic and pelagic algae and seagrasses as main primary producers. These support a diverse, high biomass, benthic community of bivalves, snails, worms and crustaceans that in turn support a multitude of waterbirds, sea turtles and fish including top predators such as shark and ray species. For many of the economically important marine predators (shrimps, crabs and fishes) the area acts as an essential nursery ground. Evidently, Barr Al Hikman is not a closed system, but is connected to adjacent lands and oceans by exchange of water, nutrients and sediments. In addition, migratory invertebrates, fishes and birds link this area with other ecosystems up to 10,000s of km's away.

Pristine coastal ecosystems such as Barr Al Hikman have become rare around the world. In many coastal systems, human activities have changed land use, habitats, the biogeochemistry and biodiversity. Logging, dredging, draining of wetlands and coastal developments are all factors that have led to marine habitat destruction. Coastal eutrophication has resulted in enhanced algal blooms followed by oxygen depletion. Fisheries have led to impoverished ecosystems in which top predators such as birds, large fishes and turtles were the first to disappear. In addition, coastal communities have also been impacted by pollutants such as PCBs and plastics and by the introduction of invasive species.

Yet, coastal areas are still among the most productive areas on the planet, providing a large number of ecosystem services to human society, including food provisioning, wave protection and tourism. Consequently, coastal areas are also the most populated areas in the world. Unravelling the key physical, chemical and biological processes that determine the productivity and ecological functioning of marine ecosystem is therefore not only scientifically challenging, but is also fundamentally important for sustainable conservation and exploitation of coastal areas. Being one of the last large relatively pristine areas in the world, Barr Al Hikman provides unique research opportunities to disentangle the complex interacting processes that shape these highly productive systems.

Significant changes are expected to affect Barr Al Hikman in the near future, including impacts from fisheries, poaching, plastic pollution and further economic and infrastructure developments along the coastline in Oman. Moreover, the area will be challenged by climate change and sea-level rise in due time. Continuing research in the area is a timely issue. To that end, we have drafted a brief proposal with several important research questions and associated approach below.

Research questions

A proper understanding of the key-processes that drive the Barr Al Hikman ecosystem will require an ecosystem-level perspective that encompasses all vital ecological components and their linkages. This report provides a first insight into the habitats that make up the system and the major processes that make it function. However, we emphasize that this remains a rather superficial first glance, and does not allow for solid predictions or recommendations on how to manage the area in light the challenges ahead. To gain such understanding, we propose well-integrated research efforts that aim to elucidate and quantify (1) habitats and species, (2) trophic interactions, and (3) connectivity.

Habitats and species

To understand the role of the various habitats (e.g. sabkha's, mangroves, dunes, non-vegetated mudflats, seagrass beds, gullies) for the Barr Al Hikman ecosystem as a whole, it is of particular importance to first determine their individual sizes, including the variation over time and space. The ecological functioning of habitats depends on its physical size and also on its quality. For the sabkha's, for example, information is required on the frequency and duration of flooding throughout the year. With respect to the intertidal areas, their quality as a habitat is also determined by emersion time, exposure to hydrodynamic forces and sediment type.
Other than assessing the spatial distribution and quality of all habitats, it is also vitally important to quantify population sizes of the most important species, as these combined make up the ecological community as a whole. Of particular interest are populations of pelagic and benthic algae, and seagrasses that determine the lower trophic level of the food web, and primary benthic consumers that form the next level and channel energy from the bottom compartment up to higher trophic levels. To fully understand the relevance of habitats for species, their habitat use at several life stages should be mapped. This should, for example, include the use of the intertidal areas as a nursery by crabs and the sabkha's as a high-tide roost by birds.

Local interactions

Getting a full grip on the richness of this area and its carrying capacity for higher trophic levels (e.g. the number of shorebirds which the region can support without environmental degradation) requires that the productivity of the biomass of primary producers is determined in time and space, as well as the efficiency of the transfer of resources and pollutants between the various levels of the food web. Understanding such variations in primary productivity requires measurements of growth conditions such as insolation and nutrient availability.
To unravel feeding interactions and energy flows within the local food web, it is first of all important to determine 'who eats whom', and secondly to quantify the strength of these interactions. Because some species might be more important than others (e.g. key-stone species), food web reconstruction of most common species should be combined with more detailed monitoring and experimental efforts on key species.
Foundation species such as seagrass, corals, and mangroves may strongly shape the coastal communities of Barr Al Hikman area by modifying their environment (e.g. restraining currents and waves, stabilization of sediments, and supplying 3D structured environments) and, therefore, deserve special attention.

Connectivity

The Barr Al Hikman area is an open system, with respect to substances (e.g. seawater, groundwater, atmospheric and oceanic nutrients and sediments) and coastal organisms (e.g. organic matter, fish, birds, turtles and mammals). At present, however, next to nothing is known about how large these fluxes are and to which extent, when and where the size of non-local populations rely on local conditions at Barr Al Hikman.
Determining and quantifying these fluxes and migrations is not only essential for a full eco-

logical understanding of the local ecosystem, but also for estimating the impacts of variations in environmental conditions in a wider area (e.g. atmospheric dust originating from the Tigris-Ephrates river Basin, fisheries in the open ocean) on the status of Barr Al Hikman.

Approach

Our understanding of the processes that interact in Barr Al Hikman is largely incomplete. This report gives directions and suggestions for future research. Above all, it illustrate that the fundamental links and feedbacks between the different components that interact in the ecosystem can only be understood by means of multidisciplinary and international research, including researches from Oman and abroad. This also requires collaboration with ongoing projects in the country. Moreover, as comparative research is an important tool to make scientific inference, it is important to seek and strengthen contacts with researchers in coastal areas all over the world.

A fundamental part of the research can nowadays be done remotely, using cutting edge research techniques. Satellite and drone images and tracking data collected over multiple years can generate enormous volumes of data that, together with model simulations, can boost immediate knowledge on several of the long-term key processes that shape the ecosystem. Yet, chapters in this report also stress the importance of more traditional research techniques, including long-term sampling programmes, field experiments and observations.

Especially the processes that are at the basis of the ecosystem at Barr Al Hikman can be mapped with high-resolution multi-annual observations such as remote sensing techniques and drone images. This includes hydrodynamics, sediment transport, primary productivity, changes in seagrass abundance and landscape morphology. These results should be interpreted with model simulations. Such models must heavily rely on ground-truthed data. This includes in situ measurements of primary producers and dust sampling stations to monitor the dust fluxes of mineral dust deposited.

Dynamics in biotic communities (benthos, birds, fishes) need to be monitored with long-term sampling campaigns. Repeated annual monitoring programs are needed to track long-term changes in the ecosystems. Monitoring at a finer temporal scale is important to understand (among others) seasonal changes in biotic communities, for instance in relation to the upwelling and red tides, but also to understand the nursery function of the area for shrimps, crabs and fishes. A short-term monitoring program is also the first step in estimating the productivity of invertebrate animals. A fundamental understanding of how the vertebrate populations are maintained (i.e. by mortality, recruitment or immigration) can be obtained by means of tagging and tracking of individual animals

To further understand the dynamics of the biotic communities it is important to understand the food web and to quantify the relative impact that species have on each other. Stable isotopic analysis can be used to construct a basic food web, substantiated with visual observations and stomach analysis. Experiments (e.g. by means of enclosures and exclosures, feeding trials) are needed to further understand how the benthic community contribute to the functioning of the intertidal ecosystem. To make this spatially explicit, tracking of higher vertebrates, including birds, fishes, crabs and turtles is required. Visual observations and tracking can also be used to study the multispecies foraging associations. Moreover, visual observations and tracking are needed to study the scale of importance of the area and to quantify the rate of connectivity with other areas.

Although the area is regarded as relatively pristine, several chapters stress that the area is not free from anthropogenic impact. Therefore, it is important to quantify the human impact on the area including spatial and temporal patterns in fishing pressure, the status of shorebirds and the cause of mortality in turtles. Together these integrated research efforts should lead to a more in-depth scientific understanding of Barr Al Hikman and coastal systems in general. Ultimately, such a jointly built knowledge base will enable informed sustainable management of one of the most pristine and productive coastal ecosystems on the planet.

– Roeland A. Bom (MSc)

NIOZ Royal Netherlands Institute for Sea Research
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Expertise: bird tracking, coastal ecology, predator-prey interactions

In 2008, Roeland visited Oman for the first time as a Master Student in a research project on shorebird ecology of Barr Al Hikman (Sultanate of Oman). After graduation at the University of Amsterdam in 2011, he immediately started his PhD project on cascading predator-prey effects in the pristine seagrass-based food web of Barr Al Hikman and will defend his PhD thesis in the course of 2018. In 2016 and 2017, he additionally worked on remote sensing and geospatial data analysis of Barr Al Hikman at the Remote Sensing Centre of the Sultan Qaboos University (Oman). At present, he is employed at NIOZ being (amongst others) involved in benthic sampling and the production of a popular scientific book on Barr Al Hikman, in cooperation with the photographer Jan van de Kam.

Selected publications:

Bom, R. A., de Fouw, J., Klaassen, R. H. G., Piersma, T., Lavaleye, M. S. S., Ens, B. J., Oudman, T. and van Gils, J. A. (2018) Food web consequences of an evolutionary arms race: Molluscs subject to crab predation on intertidal mudflats in Oman are unavailable to shorebirds. J Biogeogr, 45, 342–354

Bom, R.A., van Gils, J.A., Oosterbeek, K., Deuzeman, S., de Fouw, J., Kwarteng, A.Y. and Kentie, R. (2018). Demography of a stable population of Crab Plovers wintering in Oman. J. Ornithol.

Bom, R.A., Bouten, W., Piersma, T., Oosterbeek, K. and van Gils, J.A. (2014). Optimizing acceleration-based ethograms: the use of variable-time versus fixed-time segmentation. Movement Ecol. 2: 1–8.

– Prof. Dr. Ir. C.J.M. (Katja) Philippart

NIOZ Royal Netherlands Institute for Sea Research
Wadden Academy
Utrecht University
katja.philippart@nioz.nl, www.nioz.nl/en/expertise/waddencentre

Expertise: coastal ecology, primary productivity, bivalve life histories

In 1994, Katja defended her PhD thesis on the seagrass dynamics, based upon fieldwork in the Wadden Sea and in Mauritania. Hereafter, she studied coastal food web dynamics in general and the interactions between microscopic algae and bivalves in particular (amongst others in the Wadden Sea and the Venice lagoon). She obtained and coordinated multiple large research projects (ca. 10 MEuro in total) on, amongst others, impacts of coastal fisheries, sustainable use and conservation of marine living resources, designing multiple platforms to determine primary productivity of coastal systems, climate change impacts on the marine environment, long-term ecosystem research and shellfish aquaculture. In 2013, she became a board member (portfolio Ecology) of the Wadden Academy. The Wadden Academy aims to furnish the scientific foundations for an economically and ecologically responsible future in the Wadden Sea Region, a World Heritage Site. Since 2014, she is affiliated with the University of Utrecht, where she became a Professor on "Productivity of Coastal Marine Ecosystems" on February 2018. In March 2017, she joined the Barr Al Hikman expedition of NIOZ COS to jointly explore future research challenges.

Selected publications:

Philippart, C.J.M., van Aken, H.M., Beukema, J.J., Bos, O.G., Cadée, G.C. and R. Dekker (2003) Climate-related changes in recruitment of the bivalve *Macoma balthica*. Limnol. Oceanogr. 48, 2171–2185

Philippart, C.J.M., Anadón, R., Danovaro, R., Dippner, J.W., Drinkwater, K.F., Hawkins, S.J., Oguz, T., O'Sullivan, G., and Reid, P.C. (2011) Impacts of climate change on European marine ecosystems: Observations, expectations and indicators. J Exp Mar Biol Ecol 400, 52–69

Philippart C.J.M., Beukema, J.J., Cadée, G.C., Dekker, R., Goedhart, P.W., van Iperen, J.M., Leopold, M.F. and P.M.J. Herman (2007) Impact of nutrient reduction on coastal communities. Ecosystems 10, 187–203.

– Dr. Tjisse van der Heide

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Expertise: coastal ecology, ecological feedback interactions, food webs, modelling

Tjisse defended his PhD thesis focusing on ecological feedback mechanisms in seagrasses in 2009, after which he gradually expanded his work to include other coastal habitats. Currently, his research group primarily focuses on (1) causes and consequences of coastal ecosystem degradation, and (2) development of novel applications to preserve and/or restore coastal ecosystems. Central in the first research line is the ecosystem-level importance and functioning of habitat modifying species – also called "ecosystem engineers" or "foundation species" – that stimulate their own growth by improving their environment. Clear examples are reef-building bivalves, seagrasses, salt marsh plants, and dune-building plants that attenuate currents and waves, increase water clarity, and modify sediment conditions. Apart from these intraspecific (within species) feedbacks, he discovered that foundation species often engage in mutualistic feedbacks to further improve their growing environment. His second research line builds on the first and aims to extend fundamental findings to develop applications for preserving or restoring degrading coastal ecosystems. Examples are recent studies demonstrating that utilisation of intra- (within species) and interspecific (between species) facilitation can greatly amplify restoration yields, and the development of temporary biodegradable structures that bridge establishment thresholds for the restoration of habitat-modifying plants and bivalves.

Selected publications:

Van der Heide, T., Govers, L. L., de Fouw, J., Olff, H., van der Geest, M., van Katwijk, M, M., Piersma, T., van de Koppel, J., Silliman, B. R., Smolders, A. J. P. and van Gils, J. A. (2012) A three-stage symbiosis forms the foundation of seagrass ecosystems. Science 336: 1353–1472

Maxwell, P. S., Eklöf, J. S., van Katwijk, M. M., O'Brien, K., de la Torre-Castro, M., Boström, C., Bouma, T. J., Krause-Jensen, D., Unsworth, R. K. F., van Tussenbroek, B. I., **van der Heide, T.** (2017) The fundamental role of ecological feedback mechanisms in seagrass ecosystems – A review. Biological Reviews 92, 1521–1538

Van der Zee, E. M., Angelini, C., Govers, L. L., Christianen, M. J. A., Altieri, A. H., van der Reijden, K. J., Silliman, B. R., van de Koppel, J., van der Geest, M., van Gils, J. A., van der Veer, H. W., Piersma, T., de Ruiter, P.C., Olff. H, **van der Heide, T.** (2016) How habitat-modifying organisms structure the food web of two coastal ecosystems. Proc R Soc B, 283, 20152326

– Dr. Jimmy de Fouw

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NIOZ Royal Netherlands Institute for Sea Research
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Expertise: community ecology, food webs, biogeochemistry, consumer-resource interactions

Jim has first visit to Oman was in 2007, and was one of the initiator of a series of expeditions to Barr Al Hikman to study the ecology of wintering shorebirds in the Middle East. During the last decade he has been active in Oman and enjoying the hospitality of the Omani people during his research in Barr Al Hikman. Jim defended his PhD thesis in 2016. During his PhD he studied the bottom-up and top down forces in a tropical intertidal ecosystem in Mauritania, with a focus on seagrasses, bivalves and shorebirds. His research focusses on the community ecology of aquatic systems e.g. intertidal ecosystems, salt marches and freshwater wetlands. Foundation species (e.g. seagrass meadows, mussel reefs) play an important ecosystem-structuring role through the creation of strong bottom up effects by modifying resource availability, reducing physical stress and enhancing habitat complexity, at the same time, consumers can exert community structuring top-down effects through trophic cascades in these ecosystems. His objective of research is to transfer mechanistic understanding of ecosystems to management, which he has applied during his work in Oman. To create capacity building, he has organized several workshops Oman and in 2011 he jointly organized with the Sultan Qaboos University a conference 'Oman as a Gravitational Center in the Global Flyway Network of Migratory Shorebirds'. Currently he is advising The Ministry of Environment and Climate Affairs on nature management. In 2018 he and Roeland Bom are publishing a popular scientific book on Barr Al Hikman, in cooperation with wildlife photographer Jan van de Kam.

Selected publications:

de Fouw, J., Thorpe, A.W., Bom, R.A., de Bie, S., Camphuysen, C.J., Etheridge, B., Hagemeijer, W., Hofstee, L., Jager, T., Kelder, L., Kleefstra, R., Kersten, M., al Kiyumi, A., Nagy, S. and Klaassen, R.H.G. (2017) Barr Al Hikman, a major shorebird hotspot within the East African flyway; results of three winter surveys (2008, 2013 and 2016). Wader study, 124, 10–25

de Fouw, J., Govers, L. L., Van Belzen, J., van de Koppel, J., Dorigo, W., Christianen, M. J. A., van der Reijden, K. J., van der Geest, M., Piersma, T., Smolders, A. J. P., Olff, H., Lamers, L. P. M., van Gils, J. A., and van der Heide, T. (2016). Drought and mutualism breakdown drive landscape-scale degradation of seagrass beds. Cur Biol 26, 1051–1056.

de Fouw, J., T. van der Heide, T. Oudman, L. R. M. Maas, T. Piersma, and J. A. van Gils. (2016). Structurally complex seagrass obstructs the sixth sense of a specialized avian molluscivore. Anim Behav, 115: 55–67.

– Dr. C.J. (Kees) Camphuysen

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Expertise: marine ecology, seabird ecology, marine mammals, fisheries, GPS-tracking

In 2013, Kees defended his PhD thesis entitled 'A historical ecology of two closely related gull species (Laridae): multiple adaptations to a man-made environment' on the breeding biology and foraging ecology of two sympatric seabirds, studied in the Wadden Sea and Southern North Sea. This thesis was based on studies that commenced in 2006. Before that, most scientific work was on marine pollution and on the pelagic distribution, foraging interactions, and habitat selection of seabirds and cetaceans at sea, throughout the North Atlantic ocean, from the Antarctic to the Arctic. He obtained and coordinated several large EU research projects on the impacts of industrial (sandeels) and commercial fisheries (discards) on seabirds. Joined Barr Al Hikman expedition of NIOZ COS in March 2017 to explore future research challenges and joined Barr Al Hikman expeditions in December 2013 and Jan-Feb 2016 as part of the team surveying waders and waterbirds in the region. Further tropical research included eight multidisciplinary research cruises off the NW African coast in 2000, 2003, 2005, 2012, 2014, 2015, and 2016. Author of three books, co-author/editor of three books, author or co-author of more than 250 scientific papers since 1983. Current research interests: seabird demography and breeding, GPS tracking, tropical seabird ecology, North Sea seabird ecology.

Selected publications:

Camphuysen, C. J., Shamoun-Baranes, J., van Loon, E. E. and Bouten, W. (2015) Sexually distinct foraging strategies in an omnivorous seabird. Mar. Biol. 162: 1417–1428

Shamoun-Baranes J., Burant, J. B., van Loon, E. E., Bouten, W. and **Camphuysen, C.J.** (2016) Short distance migrants travel as far as long distance migrants in lesser black-backed gulls *Larus fuscus*. J. Avian. Biol. 47, 49–57

Donk S. van, **Camphuysen, C. J.**, Shamoun-Baranes, J. and van der Meer, J. (2017) The most common diet results in low reproduction in a generalist seabird. Ecol.Evol, 7, 4620–4629

– Dr. Ir. Ing. E.M. (Kiki) Dethmers

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Expertise: sea turtle ecology, population migration and connectivity, population genetics, marine projected area planning

In 2010, Kiki defended her PhD thesis on the ecology and phylogeography of an Australasian green turtle population with a case study for conservation from Aru, SE Indonesia. She has been involved in a wide range of marine biodiversity conservation planning and research projects, with a particular interest in sea turtle ecology and population structure. The majority of these interdisciplinary projects involved collaboration with local communities or expert groups, such as Indigenous ranger organizations in Australia or remote island communities in eastern Indonesia and other parts of Southeast Asia. With nearly 25 years of working experience in remote areas of the Indo-Pacific region, she has obtained a thorough understanding of the pressures affecting marine fauna in an environment fundamentally challenged by anthropogenic impacts including marine debris and climate change. More recently she became involved in European marine conservation that aim to support and improve the management of the UNESCO world heritage listed Wadden Sea to ensure that its unique features and values are preserved. This includes a study into the potentials shellfish aquaculture, aimed at promoting food security and sustainable agriculture. In March 2017, she joined the Barr Al Hikman expedition of NIOZ COS to jointly explore future research challenges.

Selected publications:

Butt, N., Whiting, S., and **Dethmers, K.** (2016). Identifying future sea turtle conservation areas under climate change. Biol/ Conserv. 204: 189–96

Dethmers, K. E. M. and Baxter, P. W. J. (2011). Extinction risk analysis of exploited green turtle stocks in the Indo-Pacific. Animal Conserv. 14: 140–50

Dethmers K. E. M., Broderick D., Moritz C., Fitzsimmons N. N., Limpus C.J., Lavery S., Whiting S., Guinea M., Prince R. I. T. and Kennett R. (2006) The genetic structure of Australasian green turtles (*Chelonia mydas*): exploring the geographical scale of genetic exchange. Mol Ecol 15, 3931–46

– Dr. Eelke O. Folmer

NIOZ Royal Netherlands Institute for Sea Research
Young Wadden Academy
Sky Pilot UAS
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Expertise: coastal ecology, population dynamics, spatial ecology, eco-informatics

In 2012 Eelke defended his PhD thesis on self-organization in intertidal systems. His work focused on processes underlying the spatial distributions of socially foraging shorebirds and the growth and distribution of intertidal seagrass. Eelke works at NIOZ and is a member of the Young Wadden Academy. He is co-founder of Sky Pilot UAS, a recently established consortium dedicated to effective and responsible use of unmanned aerial systems (drones) for collecting environmental data and analysis. Eelke is a broadly trained ecologist interested in the processes underlying abundance, distribution, diversity and dynamics of organisms. He believes that there is ample potential for the application of ecological theory and technology to support sustainable development and food production. He combines mathematical, statistical, computational, and eco-informatic approaches. Recent interests and activities include the application of machine learning (including deep learning) for image classification for ecological applications. He collaborates with scientists from different disciplines, including oceanographers, geomorphologists, economists and remote sensing specialists. He enjoys interacting with resource managers and conservationists to provide scientific support for effective resource management. In 2017 he joined the Barr Al Hikman expedition of NIOZ COS.

Selected publications:

Folmer, E. O., Philippart. C. J. M., van Katwijk, M., Dolch, T., Gräwe, U. and van Beusekom, J. (2016) Consensus Forecasting of Intertidal Seagrass Habitat in the Wadden Sea. J Appl Ecol 53, 1800–1813

Folmer, E. O., Geest, M. van der, Jansen, E., Olff, H., Anderson, T. M., Piersma, T. and Gils, J.A. van. (2012) Seagrass–sediment feedback: an exploration using a non-recursive structural equation model. Ecosystems, 15, 1380–1393.

Folmer, E. O., Olff, H. and Piersma, T. (2012) The spatial distribution of flocking foragers: disentangling the effects of food availability, interference and conspecific attraction by means of spatial autoregressive modeling. Oikos, 121, 551–561.

– Dr. Paolo Stocchi

NIOZ Royal Netherlands Institute for Sea Research
Paolo.Stocchi@nioz.nl, www.nioz.nl/en/expertise/nioz-sea-level-centre

Expertise: sea-level change, glacial isostatic adjustment, ice-sheets dynamics, coastal hydro- and morphodynamics

In 2007, Paolo defended his PhD thesis on the contribution of glacial and hydro-isostatic adjustment to sea-level changes in the Mediterranean Sea, on the basis of process-based numerical modelling and data analysis. During his PhD studies at the University of Bologna (Italy), Paolo contributed to the development of open source softwares that are currently employed all over the world and represent the state of the art of numerical models for sea-level changes. In 2008, Paolo started a Postdoc position at TU Delft (The Netherlands) where he developed new models that are based on non-linear and composite Earth rheologies. In 2012, Paolo moved to IMAU (Utrecht University) where he developed the very first fully-coupled ice-sheet and sea-level model that is currently employed for paleo as well as present-day and future climate-related applications. In 2013, Paolo joined the NIOZ and since 2017 he is appointed as Tenure Track Scientist. His current research focuses coastal dynamics with particular emphasis on the contribution of sea-level changes to sediment transport and coastal morphodynamics. Since 2013, Paolo is member of the PAIS (Palaeo Antarctic Ice Sheet dynamics) steering committee and is involved in several national and international cooperations and projects as well as IODP and EUROFLEETS sea-going expeditions.

Selected publications:

Stocchi, P., et al. (2017). A stalactite record of four relative sea-level highstands during the Middle Pleistocene Transition. Quatern. Science Rev., 173, 92–100

Rovere, A., Casella, E., Harris, D., Lorscheid, T., Nandasena, N.A.K., Sandstrom, M.R., **Stocchi, P.**, D'Andrea, W.J., Raymo, M. (2017). Giant boulders and Last Interglacial storm intensity in the North Atlantic. Proc. Nat. Acad. Sci. 114(46)

Stocchi, P., et al. (2013). Relative sea-level rise around East Antarctica during Oligocene glaciation. Nature Geoscience

– Dr. Jan-Berend W. Stuut

NIOZ Royal Netherlands Institute for Sea Research
jbstuut@nioz.nl
www.nioz.nl/dust

Expertise: aeolian processes, sedimentology, paleoclimatology, marine geology, marine-environmental effects of mineral-dust deposition

In 2001, Jan-Berend defended his PhD thesis at the University of Utrecht on a 300kyr climate record of southwestern Africa, based on a sedimentological study of marine sediments deposited in the Southeast Atlantic Ocean. He then moved to the University of Bremen, Germany to carry out three post-doc projects, focussing on the importance of the southern hemisphere as a driver of global climate change. Meanwhile, he developed expertise in the field of aeolian process studies, carrying out and leading both land-based field studies in Mauritania, Australia, the United Arab Emirates, and Qatar, as well as ocean-going research cruises (N=22). In 2009 he moved to NIOZ for a tenure-track position at the marine-geology department. Next to interdisciplinary projects on aeolian processes funded by the NSFs of Australia, Qatar, Germany, and the Netherlands, in 2012 he received an ERC grant to study the environmental impacts of Saharan dust deposition in the equatorial North Atlantic Ocean. So far, Jan-Berend has (co-)authored one book and 63 peer-reviewed papers. He is board member of the International Society on Aeolian Research and editorial-board member of two Elsevier journals: Aeolian Research and Quaternary International. He is affiliated to the MARUM – Center for Marine Environmental Sciences at the University of Bremen, Germany.

Selected publications:

Van der Does, M., Korte, L.F., Munday, C.I., Brummer, G.J.A. and **Stuut, J.B.W.** (2016) Particle size traces modern Saharan dust transport and deposition across the equatorial North Atlantic. Atmos Chem Phys, 16, 13697–13710

Korte, L.F., Brummer, G.J.A., van der Does, M., Guerreiro, C.V., Hennekam, R., van Hateren, J.A., Jong, D., Munday, C.I., Schouten, S. and **Stuut, J.B.W.** (2017) Downward particle fluxes of biogenic matter and Saharan dust across the equatorial North Atlantic. Atmos Chem Phys 17, 6023–6040

Guerreiro, C.V., Baumann, K.H., Brummer, G.J.A., Fischer, G., Korte, L.F., Merkel, U., Sá, C., de Stigter, H. and **Stuut, J.B.W.** (2017) Coccolithophore fluxes in the open tropical North Atlantic: influence of thermocline depth, Amazon water, and Saharan dust. Biogeosciences 14, 4577–4599

– Dr. Ir. Henk. W. van der Veer

NIOZ Royal Netherlands Institute for Sea Research
henk.van.der.veer@nioz.nl, www.nioz.nl/en/expertise/waddencentre

Expertise: coastal ecology, population dynamics, fish ecology, benthic ecology

In 1986, Henk defended his PhD thesis on regulation of the population of 0-group plaice in the Wadden Sea. Hereafter, he studied coastal food web dynamics in general with a focus on the functioning of tropical, temperate and cold water coastal systems as nursery areas for benthic and pelagic fish species. (amongst others in Puerto Rico, Guinea-Bissau, Dutch Caribbean, Dutch Wadden Sea, Norway and Iceland). He was involved in various national and international multiple research projects on, amongst others, the carrying capacity of nursery areas and the impact of climate change on fisheries. In 2006, he became head of the department of Marine Ecology at NIOZ and from 2017 onwards head of the department of Coastal Systems (COS) at NIOZ. Co-author of three books, author or co-author of more than 150 peer-reviewed scientific papers. In March 2017, he joined the Barr Al Hikman expedition of NIOZ COS to jointly explore future research challenges.

Selected publications:

Couperus, B., Gastauer, S., Fässler, S. M. M., Poos, J. J., **van der Veer, H. W.** and Tulp, I. (2016) Abundance and tidal behaviour of pelagic fish in the gateway to the Wadden Sea. J Sea Res 109: 42–51

Van der Veer, H. W. and Bergman, M. J. N. (1987). The nursery function of the western Wadden Sea. In: Tougaard S, Asbirk S (Eds.). Proc. 5th International Wadden Sea Symposium Esbjerg, 1986: Fiskeri og Sofortmuseet, Soitvandsakvariets, 123–145

Jung, A.S., Dekker, R., Germain, M., Philippart, C. J. M., Witte, J. IJ. and **van der Veer, H. W.** (2017) Decadal shifts in intertidal predator and prey communities in the Wadden Sea and consequences for food requirements and supply. Mar. Ecol. Prog. Ser. 579, 37–53

– Ibrahim Al Zakwani (MSc)

Five Oceans Environmental Services Company LLC
Higher College of Technology
Sultan Qaboos University
ibrahimaz@hotmail.co.uk

Expertise: benthic sampling, coastal ecology, predator-prey interactions, food webs construction using stable isotopes

In March 2015, Ibrahim visited Barr Al Hikman intertidal marine wetland nature reserve (Sultanate of Oman) for the first time as a field sampling assistant with a B.Sc. in Environmental Biology (Graduated in Feb 2015). He joined the research teams at Barr Al Hikman in the field works for bird and benthic sampling. After graduation at Sultan Qaboos University in Oman in 2015, he immediately started his master's degree project entitled ''Estimating the proportional contribution of seagrass and benthic diatoms to the diet of the benthic organisms in Barr Al Hikman marine intertidal ecosystem using δ^{15}N and δ^{13}C stable isotopes'' in September 2015. In summer 2016, Ibrahim visited the Netherlands as intern in NIOZ (Royal Netherlands Institute for Sea Research) to continues with his master project sample analysis for δ^{15}N and δ^{13}C stable isotopes, and he joined in some field works related to bird sampling. At present, Ibrahim is working as a junior consultant at Five Oceans Environmental Services Company and a part time lecturer at Higher College of Technology in Oman. Also, he is being (amongst others) involved in benthic sampling and the production of a popular scientific book on Barr Al Hikman, in cooperation with the photographer Jan van de Kam.

– Appendix
Track record since start of scientific work in Barr Al Hikman (2007)

Scientific output

published (including papers using data gathered by the team in Barr Al Hikman):

Bom, R. A., de Fouw, J., Klaassen, R. H. G., Piersma, T., Lavaleye, M. S. S., Ens, B. J., Oudman, T. and van Gils, J. A. (2018) Food web consequences of an evolutionary arms race: Molluscs subject to crab predation on intertidal mudflats in Oman are unavailable to shorebirds. J Biogeogr, 45, 342–354

Bom, R.A., van Gils, J.A., Oosterbeek, K., Deuzeman, S., de Fouw, J., Kwarteng, A.Y. and Kentie, R. (2018). Demography of a stable population of Crab Plovers wintering in Oman. J. Ornithol.

de Fouw, J., Thorpe, A.W., Bom, R.A., de Bie, S., Camphuysen, C.J., Etheridge, B., Hagemeijer, W., Hofstee, L., Jager, T., Kelder, L., Kleefstra, R., Kersten, M., al Kiyumi, A., Nagy, S. and Klaassen, R.H.G. (2017) Barr Al Hikman, a major shorebird hotspot within the East African flyway; results of three winter surveys (2008, 2013 and 2016). Wader study, 124, 10–25

de Fouw, J., R. A. Bom, W. Hagemeijer, and R. H. G. Klaassen. 2016. Barr Al Hikman, a major shorebird hotspot
within the West Asian East-African flyway; results of three winter surveys. Online report.

Bom, R. A., and al-Nasrallah, K. (2015) Counts and breeding biology of Crab Plovers *Dromas ardeola* on Bubiyan Islands, Kuwait, in 2012–2014. Wader study 122:212–220.

Kwarteng, A. Y., Bom, R. A., and van Gils, J. A. (2015) Crab Plover Dromas ardeola movement and migration at Barr Al Hikman, Sultanate Oman. Conference: 5th International Conference on Estuaries and Coasts (ICEC2015), Muscat, Oman.

Bom, R.A., Bouten, W., Piersma, T., Oosterbeek, K. and van Gils, J.A. (2014). Optimizing acceleration-based ethograms: the use of variable-time versus fixed-time segmentation. Movement Ecol. 2: 1-8.

van Roomen, M., Langendoen, T., Amini, H., de Fouw, J., Mundkur, T., Thorpe, A., and Ens B. J. (2014) Population estimate of *Haematopus ostralegus longipes* based on non-breeding numbers in January. Wader study group bulletin 20:41–46.

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Gommer, R. Bom, R.A., Fijen, T.P.M. and van Gils, J.A. in revision with PLoS One. Stomach fullness shapes prey choice decisions in crab plovers (*Dromas ardeola*)

Bom, R.A., Fijen, T.P.M. and van Gils, J.A. Wait a minute? Hiding behaviour of burrowing crabs explains why crab plovers *Dromas ardeola* prefer vigorous swimming crabs

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Bom, R. A., and Ebbinge, M. in prep. Simple and complex burrow constructions of two *Macrophthalmus* species on the intertidal mudflats of Barr Al Hikman, Sultanate of Oman.

Identified species list

A list of species which are identified during the expeditions is available on request, please contact the editors of the report.

PhD students and MSc. Students

R. A. Bom	2011 - now	PhD student, Royal NIOZ, Groningen University
I. A. K. Al Zakwani	2015 - 2017	Msc. Student, Sultan Qaboos University
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T. Fijen	2012 - 2013	Msc. Student, Royal NIOZ, Groningen University
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Project	year	PI and organizers	Institutes	Total amount (OMR)	Funders
Pilot expedition to explore challenges for future research	2017	Prof. K. Philippart (PI), Mr. R. A. Bom (organizer), Dr. J. de Fouw (organizer),	NIOZ, Radboud University	-	NIOZ, Radboud university
Bird monitoring of Barr Al Hikman, Sultanate of Oman.	2017	Mr. W. Hagemeijer (PI), Dr. J. de Fouw (co-PI)	Wetlands International, Radboud University	-	Shell Development Oman
Bird monitoring of Barr Al Hikman, Sultanate of Oman.	2016	Mr. W. Hagemeijer (PI), Dr. J. de Fouw (contributing organizer)	Wetlands International	-	Shell Development Oman
Remote Sensing and Geospatial Data Analysis of Barr Al Hikman Intertidal Ecosystem: Implications of Cascading Predator-prey Effects in a Pristine Seagrass-based Food Web	2013 - now	Dr. A. Kwarteng (PI), Prof. Dr. R. Victor (co-PI), Dr. J. van Gils (collaborator), Mr. R. A. Bom (PhD)	Sultan Qaboos university (SQU), NIOZ	139.700	The Research council (TRC)
Bird monitoring of Barr Al Hikman, Sultanate of Oman.	2013	Dr. J. de Fouw (PI), Mr. A. Thorpe (co-PI), Prof. Dr. R. Victor (collaborator)	NIOZ, SQU	3.800	Embassy of the Kingdom of the Netherlands (Oman), Carex Holland, Swedish Ornithology Union (SOF)
Workshop: Strengthening the International Waterbird Census in Oman	2013	Dr. J. de Fouw (PI), Mr. A. Thorpe (co-PI)	NIOZ, Wetlands International	650	Wetlands International
Cascading predator-prey effects in a pristine seagrass-based food web	2011-2015	Dr. J. van Gils (PI), Mr. R. A. Bom (PhD), Dr. A. Kwarteng (collaborator), Prof. Dr. R. Victor (collaborator)	NIOZ, SQU	110.000	The Dutch Organisation for Research (NWO)
An International Conference on Oman as a Gravitational Center in the Global Flyway Network of Migratory Shorebirds	2011	Dr. M. Ahmed (organiser), Dr. J. de Fouw (organiser), Prof. Dr. R. Victor (co-organiser)	NIOZ, SQU	5.300	Shell Development Oman

Project	year	PI and organizers	Institutes	Total amount (OMR)	Funders
The importance of Barr Al Hikman (Oman) as a spring stopover site for migratory shorebirds in the Middle East - East African migratory flyway	2010	Dr. J. de Fouw (PI), Mr. A. Thorpe (co-PI), Prof. Dr. R. Victor (collaborator)	NIOZ, SQU	6.100	Shell Development Oman, The Royal Netherlands Institute for Sea Research (NIOZ), Natural Research (Scotland), Erasmus University (the Netherlands), Linnaeus University (Sweden)
Ecological shorebird research in a tropical intertidal seagrass ecosystem, part 2	2009	Dr. J. de Fouw (PI), Dr. R.H.G. Klaassen (co-PI) Mr. A. Thorpe (co-PI), Prof. Dr. R. Victor (collaborator)	The Working Group International Waterbird and Wetland Research (WIWO	8.100	Shell Development Oman, Embassy of the Kingdom of the Netherlands (Oman), Natural Research (Scotland), Erasmus University (the Netherlands), Swedish Ornithology Union (SOF)
Ecological shorebird research in a tropical intertidal seagrass ecosystem, part 1	2008	Dr. J. de Fouw (PI), Dr. R.H.G. Klaassen (co-PI) Mr. A. Thorpe (co-PI), Prof. Dr. R. Victor (collaborator)	WIWO	6.100	Embassy of the Kingdom of the Netherlands (Oman), Petroleum Development Oman (PDO), Natural Research (Scotland), Swedish Ornithology Union (SOF), Ornithology Society of the Middle-East (OSME)
Ecological shorebird research in a tropical intertidal seagrass ecosystem, pilot study	2007	Dr. J. de Fouw (PI), Dr. R.H.G. Klaassen (co-PI) Mr. A. Thorpe (co-PI), Prof. Dr. R. Victor (collaborator)	WIWO	2.800	Natural Research (Scotland), Swedish Ornithology Union (SOF), Ornithology Society of the Middle-East (OSME), Wetlands International

Colophon

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Jimmy de Fouw - page: 26,46
Roeland Bom - page: 22
Kiki Dethmers - page: 74 (picture taken in Australia, Crocodile island)

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In this report, marine scientists affiliated with the NIOZ Royal Netherlands Institute for Sea Research and Radboud University summarize the current state of knowledge and denote future research challenges on various characteristics of the Barr Al Hikman (Sultanate of Oman) coastal ecosystem.

The Royal Netherlands Institute for Sea Research (NIOZ) is the national oceanographic institute and principally performs academically excellent multidisciplinary fundamental and frontier applied marine research addressing important scientific and societal questions pertinent to the functioning of oceans and seas. Second, NIOZ serves as national marine research facilitator (NMF) for the Netherlands scientific community. Third, NIOZ stimulates and supports multidisciplinary fundamental and frontier applied marine research, education and marine policy development in the national and international context.

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