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Transdisciplinary synthesis for ecosystem science, policy and management: The Australian experience

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HIGHLIGHTS

- Structured synthesis advances science through transdisciplinary collaboration.
- Synthesis centres can effectively facilitate transdisciplinary synthesis.
- Syntheses draw on unifying frameworks, culturally resonant narratives and big data.
- Benefits include conceptual, methodological, policy, career and research outcomes.
- Continuity of programmes is essential to fully reap their benefits.

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ABSTRACT

Mitigating the environmental effects of global population growth, climatic change and increasing socio-ecological complexity is a daunting challenge. To tackle this requires synthesis: the integration of disparate information to generate novel insights from heterogeneous, complex situations where there are diverse perspectives. Since 1995, a structured approach to inter-, multi- and trans-disciplinary[1] collaboration around big science questions has been supported through synthesis centres around the world. These centres are finding an expanding role due to ever-

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[1] Transdisciplinary: A theory, methodology, point of view or perspective that transcends entrenched categories and engages both researchers and practitioners in formulating problems in new ways to address real-world problems (e.g. eco-health, ecosystem services).

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Synthesis centre

accumulating data and the need for more and better opportunities to develop transdisciplinary and holistic approaches to solve real-world problems. The Australian Centre for Ecological Analysis and Synthesis (ACEAS <http://www.aceas.org.au>) has been the pioneering ecosystem science synthesis centre in the Southern Hemisphere. Such centres provide analysis and synthesis opportunities for time-pressed scientists, policy-makers and managers. They provide the scientific and organisational environs for virtual and face-to-face engagement, impetus for integration, data and methodological support, and innovative ways to deliver synthesis products.

We detail the contribution, role and value of synthesis using ACEAS to exemplify the capacity for synthesis centres to facilitate trans-organisational, transdisciplinary synthesis. We compare ACEAS to other international synthesis centres, and describe how it facilitated project teams and its objective of linking natural resource science to policy to management. Scientists and managers were brought together to actively collaborate in multi-institutional, cross-sectoral and transdisciplinary research on contemporary ecological problems. The teams analysed, integrated and synthesised existing data to co-develop solution-oriented publications and management recommendations that might otherwise not have been produced. We identify key outcomes of some ACEAS working groups which used synthesis to tackle important ecosystem challenges. We also examine the barriers and enablers to synthesis, so that risks can be minimised and successful outcomes maximised. We argue that synthesis centres have a crucial role in developing, communicating and using synthetic transdisciplinary research.

1. Introduction

The rapid increase of human impacts on the world and compounding environmental and social costs have been paralleled by an acceleration of data and knowledge generation. This ever-increasing volume and complexity of scientific data, along with an emphasis on reductionism, has favoured scientific specialisation and knowledge fragmentation (Sidlauskas et al., 2010; Hampton and Parker, 2011). The complexity and profundity of current environmental challenges, however, requires solutions that transcend traditional disciplinary boundaries and synthesise knowledge (Carpenter et al., 2009).

Synthesis is necessary to integrate disparate, often incomplete, information from multiple sources, sectors and disciplines, and to enable extrapolation over large spatial and temporal scales. Synthesis enables the development of new models and hypotheses that can address complexity and lead to improved environmental awareness, understanding and solutions to problems (Peters, 2010; Hampton and Parker, 2011; Kemp and Boynton, 2012). The need for synthesis to tackle environmental challenges has been recognised and responded to internationally by, *inter alia*, the IPCC (Intergovernmental Panel on Climate Change), IGBP (International Geosphere-Biosphere Programme), IHDP (International Human Dimensions Programme on Global Environmental Change), and recently through the linking of these under Future Earth.[2]

Since 1995, synthesis centres have been established around the world to provide a structured approach to inter-, multi- and trans-disciplinary collaboration around big science questions. In contrast to the broad synthesis scope and stakeholder engagement undertaken by the large international synthesis groups, in this paper we focus on ecological synthesis through national and regional synthesis centres. The focus is largely on transdisciplinary integration of biophysical and linked social science (and a certain range of disciplines within this domain) in connection with environmental policy and management. We define transdisciplinary research to mean research involving multiple scientific disciplines in collaboration with policy and management (not solely citizen or community engagement). This contrasts with interdisciplinary research which we take to mean research between academic disciplines in a non-additive or non-transformational way, and multidisciplinary research as research between academic disciplines in an additive manner.

First, we describe the term synthesis and the need for transdisciplinary synthesis to address complex environmental problems. Next, we provide an overview of synthesis centres globally, and focus on the Australian Centre for Ecological Analysis and Synthesis (ACEAS) to demonstrate the capacity for synthesis centres to facilitate trans-organisational, transdisciplinary synthesis. We conclude by discussing the lessons learned from the ACEAS experience about how to overcome barriers to synthesis and to maximise the benefits and desired outcomes.

1.1. What is synthesis?

There is no single synthetic approach to science (Sidlauskas et al., 2010; Cooper et al., 2009) and there are many definitions of synthesis in the scientific literature (Kemp and Boynton, 2012). Scientific synthesis generally relates to an inductive process of integrating disparate elements (i.e. concepts, data, methods, analytical results) from one or more disciplines, to develop a novel integrative insight or model as a primary outcome (Sidlauskas et al., 2010). Synthesis can be systematic and tied to particular methodologies that are quantitative, such as through meta-analyses, or qualitative (Cooper et al., 2009). In its simplest form, 'synthesis' is a creative activity in which the aim is to produce new insights or outcomes that are greater and more meaningful than the constituent parts.

There has been a long history of knowledge integration in ecology, which may have made it easier for ecologists and environmental scientists to embrace synthesis. The discipline of ecology is unlike the more mechanistic physical sciences in that a single process is unlikely to be applicable everywhere and for all time. The search for relatively simple, quantifiable and universal relationships and laws therefore has been challenging and remains unresolved (Cooper, 2003). Ecology is inherently complex due to the variability of its elements across spatio-temporal scales, and so is more a probabilistic than deterministic science. As ecology has matured, understanding has increasingly been facilitated through meta-analyses and syntheses of many studies to produce more general understanding. Similarly, the social sciences also have strived to combine results of disparate studies to understand complex problems; for example, in society and medicine (Cooper et al., 2009).

1.2. The need for synthesis

Effective, informed environmental policy and management needs an evidence base which can be provided through synthesis of existing information. Environmental problems encompass multi-scaled and often multi-jurisdictional complexity, thus requiring inputs from many disciplines, sectors and stakeholders. It is critical not only to understand the biophysical drivers that underpin species persistence or habitat sustainability, but also the dynamics of drivers operating in the social and economic domains, and disparate stakeholder perspectives.

Transdisciplinary synthesis provides a way to integrate disparate knowledge to inform evidence-based policy and practical, feasible management responses. Transdisciplinary research that integrates multiple forms of knowledge and perspectives through participatory engagement, particularly on issues with high stakes and uncertainty, is more

[2] http://www.futureearth.org/.

likely to effectively address complex environmental problems than disciplinary, cross- or inter-disciplinary approaches (Patterson et al., 2013).

Transdisciplinary synthesis can be extremely challenging because it requires bridging of the long-acknowledged disconnect between scientific, management, policy and broader community sectors (e.g. Ryder et al., 2010; Sutherland et al., 2012). These sectors have philosophical and practical differences in cultures, measures of success, rewards, feedbacks and time cycles (Table 1). Further, there are different disciplinary perspectives and traditions (e.g. research context and motivation, world-views, linguistics) to be surmounted (Eigenbrode et al., 2007; Ens et al., 2012).

Consequently, transdisciplinary synthesis requires interaction between scientists who understand and can evaluate the science, and policy-makers and managers who understand the policy context or management complexity. Moreover, each perspective needs to be given equal credence in the crafting of optimal synthesis outcomes, something that can be very difficult to achieve because each stakeholder favours the validity of 'their' perspective.

Effective policy develops through the input of multiple forms of knowledge, including systematic research such as scientific analysis (but also demographic, economic, etc.), programme management experience ('practice'), bureaucratic or political judgement, and civic or community knowledge (Head, 2008; Pohl, 2008). Policy development is often dominated by multi-faceted, short-term priorities (Lawton, 2007) with outcomes based on judgement, practical considerations, cultural values, economics, user interests, community perceptions and, where feasible, scientific knowledge (Lawton, 2007; Ryder et al., 2010). Public policy and environmental management are sometimes characterised as 'the art of the possible' and of necessity have untidy edges of imperfection and compromise in order to be implementable in a societal context. From the perspective of a policy officer, the scientific method of inquiry often contributes to uncertainty and leads to a reluctance to act, driven as it is by continuing contestability, exactness and refinement.

Policy is frequently framed in general terms and not well understood by the scientific community, especially since scientific or other forms of knowledge is sought and used in multiple ways by governing bodies (Howlett et al., 2009; Dovers and Hussey, 2013). The scientific process is driven by a need for observational and experimental evidence, with scientists investigating specific questions and testing hypotheses over longer timeframes than typically are needed to make policy or management decisions. Scientists are keen to see their science inform policy and management, but their professional reward system is based on publications (Laurance et al., 2013) with few institutional incentives to encourage knowledge-transfer (Shanley and López, 2009). Moreover, there are few opportunities to engage directly in discussion on policy implications of research outcomes. Consequently, most scientists focus on publishing their work in scientific journals without fully engaging with the process of developing 'evidence-based-policy'.

Managers, in applying new knowledge to their areas of responsibility, can form a bridge between policy-makers and scientists; they often have direct experience of policy application and can validate scientific understanding through their observations and experience. The paradigm of each sector dictates the approach to knowledge acquisition (Table 1) and influences the approach to environmental issues.

These comparisons are generalisations, but are nevertheless useful to highlight that there are different perspectives, and a different emphasis when the synthesis process is used to resolve management problems rather than solely to improve scientific knowledge. Synthesis centres provide a forum in which a structured process of collaboration to develop new knowledge and approaches as a collective endeavour can help to bridge sectoral, disciplinary and cultural divides (Pohl, 2008; Ens et al., 2012).

1.3. Transdisciplinary synthesis centres — their practice and achievements

The number of synthesis centres has been increasing globally, especially in the last decade, due to their effectiveness in coordinating complex synthesis projects (Fig. 1). To date, there have been more than a dozen synthesis centres across North America, Europe, China and Australia, spreading from their ecological origins to biomedical sciences, mathematics, earth sciences and genomics. These centres foster collaborative synthesis by bringing groups of people together for blocks of time in a collegial setting. Their common aim is to stimulate creative thinking and group learning with the technological support to synthesise and analyse diverse datasets to address critical science questions.

Synthesis centres are designed to motivate subject specialists to 'think outside their disciplinary box' when addressing questions of significance in science, policy and management. Initially, participants are encouraged to rapidly appraise each other's perspectives. Pennington et al. (2013, p. 570) described this process:

> *Through critical reflection and reflective discourse with collaborators, they connect the new concepts to their own understanding; revise their mental models; and expand the conceptual, data, or technical foundations of their own discipline. This occurs concurrently among the collaborators. Once this has been achieved, they are able to collectively synthesize their new understanding into integrated conceptual frameworks that draw on deep knowledge from all disciplines, providing innovative research opportunities for all of the collaborators.*

Nonetheless, synthesis centres vary in their emphasis; the Chinese Ecosystem Research Network (CERN) has focused on internal stakeholder needs, whereas the National Center for Ecological Analysis and Synthesis (NCEAS) in the USA focused on external stakeholder demands

Table 1
Contrasting emphases in characteristics of ecological scientists, policy-makers and environmental managers towards knowledge acquisition and its use (based on the authors' knowledge and experience).

Characteristic	Scientists	Policy-makers	Managers
Goal	Knowledge generation	Long-term strategic direction/short-term socio-political and economic imperatives	Informed decision-making, compliance with policy and regulatory settings
Level of detail sought	High	Low	Low–moderate
Acquiring knowledge	Cumulative	When needed	When needed/cumulative
Breadth of knowledge	Specialised/expert	Broad/generalised	Broad/generalised/applied; locally specific
Motivation	Curiosity and solutions focused	Target oriented	Target oriented/curiosity and solutions focused
Longevity in specific role	Long	Short	Medium–long
Perception of time	Longer term, varies with natural phenomena and with funding or contract cycles	Shorter term, with policy and political cycles and programme budget periods	Driven by seasonal and climatic cycles and markets, policy and management plans, and budget constraints
Expectation for validity of knowledge	Hard (quantified), peer review	Multiple forms of evidence and inputs	Hard, experiential, feedback from experience

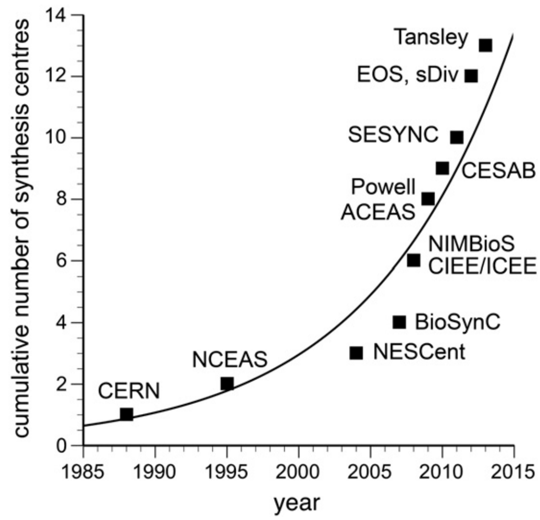

Fig. 1. A graph of emergence of synthesis centres throughout the world. (Explanation of acronyms can be found in Table 2. More information and links to centre websites can be found on www.synthesis-consortium.org).

(Table 2). The measurable outputs of the various synthesis centres (Table 2) demonstrate their intended benefits to knowledge-generation, connectedness and research.

The Australian Centre for Ecological Analysis and Synthesis (ACEAS) operated from 2009 to mid-2014 as a virtual and physical facility within the Terrestrial Ecosystem Research Network (TERN). TERN was created by the Australian (national) government, with support from the Queensland and South Australian (state) governments, in 2009 to coordinate improved collaboration among ecosystem scientists and improved data integration across disciplines.[3] ACEAS more specifically aimed to provide disciplinary and interdisciplinary integration, synthesis and modelling of ecosystem data for the purpose of informing and advancing evidence-based environmental management strategies and policy at regional, state and continental scales. There were two objectives: to integrate disparate data thereby advancing science and evidence-based policy; and to effectively communicate scientific knowledge to managers and policy-makers. By embedding managers within synthesis groups, it was intended that practical transdisciplinary outcomes would be achieved, with greater relevance and potential for implementation in policy and planning.

Despite limited funding and staff, and no fixed location for synthesis meetings, ACEAS supported 43 working groups and a sabbatical fellowship to work on questions relating to biodiversity, water and management. The 730 participants and 225 organisations engaged across 65 analysis and synthesis activities. Prior to this Special Issue, these ACEAS working groups had produced 18 refereed journal papers from 52 group meetings of three to five days each, along with data and methodological benefits and outcomes. There have been over 28 conference presentations, a keynote address, three independent websites, eight data visualisations published, and three software applications.

In addition to these measured outputs, there have been many indirect outcomes, including enhancement of collaborative networks, and the influence of working group methods and findings on science, policy and management (Section 2). Two working groups provided advice directly to government, but there also have been almost 80,000 unique visitors to the ACEAS website since 2012. ACEAS has exemplified national leadership in analysis and synthesis of environmental data to support future management and policy needs (ACEAS, 2014). It has been a key developer of innovative environmental management and knowledge brokering, with publications encompassing carbon accounting, ongoing fauna declines, extinction risk, invasive species, integrated catchment planning, governance and risk analysis, drought-related tree mortality, forest fire management, Indigenous bio-cultural knowledge, and landscape change.

2. Synthesis centres in action

The operation of synthesis centres is generally characterised by the following ten criteria, with each demonstrated by working groups to varying degrees:

1. Enhanced data sharing;
2. Enhanced collaboration and networking;
3. Enhanced performance and productivity;
4. Enhanced transdisciplinarity;
5. Enhanced theoretical and analytical understanding;
6. Stimulation of conceptual advances;
7. Stimulation of methodological advances;
8. Multi-forum communication of outputs;
9. Transformation of scientific narratives into community dialogues; and
10. Embracing feedback and evaluation.

In this section, we show how synthesis centres promote these criteria. We discuss Australian and international examples, with a highlight on ACEAS (using information from feedback obtained throughout its life (Section 2.10), interviews, reports, and papers in this Special Issue).

2.1. Enhanced data sharing

Fundamental to the emergence of new information and knowledge is access to existing data. However, data are often not shared and statistical codes not reported, even when data sharing is required as part of publishing conditions (Savage and Vickers, 2009; Alsheikh-Ali et al., 2011). This is not necessarily due to author reluctance but partly due to the inevitable erosion of author-stewarded data and a lack of resources to share and manage datasets (Michener et al., 1997); Vines et al. (2014) showed that 17% of datasets and 7% of author emails disappear per year. Data may become undiscoverable due to the compiler moving offices or careers, a lack of centralisation of the data repository, or the data missing appropriate descriptive information (metadata), as noted by the ACEAS animal telemetry working group (Campbell et al., 2015–in this issue). Individual researchers often manage data on a private computer without having a long-term preservation strategy, thereby increasing the risk of data loss.

Governments and funding bodies now strongly encourage re-use of publicly funded research data. However, data re-usability depends on adequate metadata documentation that facilitates searching, locating and accessing of data relevant to addressing a key question (Valdecasas and Correas, 2010; Dwyer et al., 2015). There is a growing effort in the research community through initiatives like DataCite (Brase et al., 2015) to assist researchers to locate and cite research datasets using Digital Object Identifiers (DOIs) assigned to the dataset. In Australia, national initiatives like TERN (and its facility, ACEAS), the Integrated Marine Observing System (IMOS),[4] Australia's Virtual Herbarium (AVH)[5], and the Atlas of Living Australia (ALA)[6] have enabled public access to terrestrial, marine and biodiversity data described using domain-specific metadata standards. This has significantly improved the availability of data and their potential for use in innovative research applications.

Many ACEAS working groups combined their own datasets with public or open-source data to analyse broad-scale ecological patterns. Despite the advantages of data-openness, there were a number of impediments to sharing (Specht et al., 2015–in this issue). Some data owners were apprehensive of others misusing or inadequately acknowledging

[3] http://www.tern.org.au/What-is-TERN-pg22570.html.

[4] https://imos.aodn.org.au/imos123/.

[5] http://avh.chah.org.au/.

[6] http://www.ala.org.au/.

Table 2
Vital statistics of international synthesis centres active in 2014 arranged from the oldest centre to the newest centre. (The information presented is based on the centres' websites and authors' knowledge. More information and links to centre web sites can be found on www.synthesis-consortium.org).

Centre (acronym)	Location	Audience	Measurable outputs
Chinese Ecosystem Research Network (CERN)	China	Ecosystem services, ecological processes of water, C, N, ecological assessment	Publications, demonstrations, support for participant organisations
National Center for Ecological Analysis and Synthesis (NCEAS)	USA	Ecology, environmental sciences	Number of publications, participation rates, promotion of collaboration, postdoctoral success, ecoinformatics research, improved data access, education, community outreach
National Evolutionary Synthesis Center (NESCent)	USA	Evolutionary biology and the social sciences, evolutionary medicine, ecology, education, astrobiology	Number of publications and citations, successful grant funding, publicly available software/databases, stimulation of open science and open access, fostering new collaborations, uptake in non-traditional disciplines
Biodiversity Synthesis Center (BioSync)	USA	Biodiversity sciences, particularly those involved with the Encyclopedia of Life	Outputs relevant to biodiversity science and education
National Institute for Mathematical and Biological Synthesis (NIMBioS)	USA	Interface between biology and mathematics	Career choices of participants, outcomes (e.g. papers, websites, curricula, new collaborations, grant proposals), attendance and demographic statistics
Canadian Institute of Ecology and Evolution (CIEE/ICEE)	Canada	Ecology, environment and evolution in aquatic and terrestrial ecosystems	Attendance at workshops and training programmes, collaborative partnerships created, refereed publications, 'white paper' reports. Internal evaluation from CIEE Management Board
John Wesley Powell Center for Analysis and Synthesis	USA	Earth system science: physical and environmental questions	Participation, publications, research grant funding
Australian Centre for Ecological Analysis and Synthesis (ACEAS)	Australia	Ecosystem science, management and policy	Participation demographics, numbers of papers, research grants, reports and presentations to peer-groups, citations, synthesised data deposition, network creation and enhancement
CEntre for the Synthesis and Analysis of Biodiversity (CESAB)	France	Biodiversity sciences, ecology	Participation in working groups, training workshops, postdocs, internships, partnerships; publications; seminars; synthesised databases; knowledge dissemination
National Socio-Environmental Synthesis Center (SESYNC)	USA	Ecologists, sociologists, political scientists, economists, psychologists, policy-makers, planners and designers	Creation of new coalitions, learning at all levels, expansion and improvement of the synthesis process, and creation of a flexible, adaptive institution
Environmental 'Omics Synthesis Centre (EOS)	UK	Environmental 'Omics e.g. bioinformatics, genomics, metagenomics, phylogenetics, epigenetics, metabolomics, evolutionary ecological Omics	Support for the wide range of current investments in 'Omics and strategic oversight at the community level
The Synthesis Centre for Biodiversity Sciences (sDiv)	Germany	Biodiversity sciences and management	High-impact publications, proposals for innovative research grants, standard protocols, experimental designs for all aspects of biodiversity research
Tansley Working Groups	UK	Biodiversity and resource management	Publication or other concrete forms of outputs, knowledge transfer, professional development of early career researchers

their data. Others were concerned that their substantial investment of time and effort could be unethically exploited for greater rewards by subsequent users, or that data would be unfairly scrutinised to the detriment of the collector's reputation.

Synthesis centres like ACEAS, champions of data sharing and its advantages, can help overcome the reluctance to share data through ensuring that (i) Intellectual Property (IP) of data owners is recorded and acknowledged, (ii) research results (and data) are published, and (iii) a safe experience of sharing or re-using data is provided (Specht et al., 2015–in this issue). As people get used to sharing, behavioural resistance breaks down and the benefits become increasingly recognised. Sharing primary data increases the citation rate of the source articles, regardless of journal impact factor, publication date, or author country of origin (Piwowar et al., 2007).

A pertinent example of data mobilisation comes from the DIVGRASS working group of the French Centre CESAB. This working group compiled more than 50,000 floristic relevés from grasslands across France from a variety of sources, a substantial proportion of which were in non-academic and protected repositories. This extensive compiled dataset enabled the group to answer a long debated question pertaining to the relationship between species diversity and environment (Violle et al., 2015–in this issue).

2.2. Enhanced collaboration and networking

Although the complexity of today's conservation challenges often requires collaborative transdisciplinary research to generate new knowledge and approaches, researchers and managers often lack the time and capacity to explore diverse expert and stakeholder opinions. For managers and decision-makers, collaboration across sectors increases potential uncertainty and requires expertise many do not possess (Wyborn and Dovers, 2014). One working group participant reported that 'without the assistance of ACEAS, gathering such a diverse group would not have been possible' (ACEAS e-newsletter December 2013).[7] Another remarked that the rare opportunity to gather such a multi-disciplinary group together, particularly for an extended time, had been a highlight for him (ACEAS e-newsletter March 2012).[8]

Without the research structure of a synthesis centre (i.e. physical and virtual meeting spaces with technical and logistical support), it can be difficult to bridge the gulf between academia and policy or management in a systematic way. Such challenging issues can be addressed

[7] http://www.aceas.org.au/newsletters/dec2013/aceas-dec13.html.
[8] http://www.aceas.org.au/newsletters/march/ACEAS-March.html.

through multiple meetings of small working groups, facilitated by synthesis centres. An environmental manager who participated in two ACEAS working groups confirmed that such collaboration is generally acknowledged as important, but 'does not occur without significant coordination, effort and resourcing' (ACEAS e-newsletter June 2013).[9]

By facilitating trans-organisational engagement, synthesis centres increase the potential for trans-organisational innovation (Millar et al., 1997). ACEAS provided a platform whereby policy-makers, environmental managers, Indigenous knowledge custodians, academics and students worked closely together to co-develop ideas and identify knowledge gaps. Knowledge distributed across disciplines and spatially dispersed organisations was brought together, encouraging the development of practical outcomes directly relevant in an applied setting. Such collaboration promotes multi-directional knowledge exchange; it encourages the uptake of scientific theory into new management strategies and the development of innovative, scientifically informed solutions to applied environmental management problems of contemporary policy relevance.

The ACEAS format of intensive, face-to-face workshops provided a collegial atmosphere that engaged and intellectually stimulated participants. A number of the products relied heavily on serendipity and creative inspiration during informal moments, motivating participants to continue working on projects out-of-session. The synthesis centre's virtual meeting spaces and technical/logistical support were used to update and communicate project progress and products. Key benefits identified by participants in discussions and online surveys included the collective harnessing of expertise, expanded networks, and ongoing collaborations. For example, all but two of the 14 members of one early ACEAS working group ('A Cup Half Full? Thresholds and Regime Shifts in Australian Freshwater Ecosystems') expanded their research networks through participation in additional ACEAS working groups; one member contributing to four working groups. Many participants continued working with researchers and government officers from Australia and other countries on applied conservation projects after the working groups had completed their project cycle (Weber et al., 2013).

2.3. Enhanced performance and productivity

While focused on providing opportunities for synthetic collaboration between Australian and international researchers, ACEAS encouraged broader community dialogue in a number of ways. These included:

(a) supporting working groups with broad interdisciplinary and/or transdisciplinary foci that included end-users in the process (e.g. understanding Australian aerobiology to monitor environmental change and human allergenic exposure (Davies et al., 2015–in this issue), integrated catchment to coast planning, and ecosystem services in northern Australia and adjacent regions);
(b) supporting working groups with a cross-cultural focus (e.g. Australian Indigenous bio-cultural knowledge, Pert et al., 2015–in this issue);
(c) 'grand workshops', which brought together several working groups to facilitate further synthesis and collaboration (e.g. Bradshaw et al., 2013; Davis et al., 2015–in this issue), and included public events such as the 2014 live-streamed (broadcast) 'hypothetical';
(d) a publicly accessible, interactive internet portal providing spatial visualisation and other illustrative information relating to working group outcomes, including those of the Indigenous biocultural knowledge working group (Section 2.8); and
(e) use of social media (Section 2.8).

While some outputs from ACEAS working groups might have been developed without ACEAS intervention, this would probably have been at a slower rate and smaller scale due to lesser capacity for data collation, analysis and participatory collaboration. One researcher remarked that their progress had been greater than expected, due to 'individual dedication, team cohesion, [the] positive environment created by ACEAS, as well as the exciting and fertile nature of [the] transdisciplinary research', and because of the luxury to focus on the work disengaged from other responsibilities (ACEAS e-newsletter December 2013).[10] There was value-adding too, with another working group being able to 'collate and add value to data from long-term experimental trials, thus increasing returns on the original investment' (ACEAS e-newsletter December 2011).[11]

The focused working group process also benefited early career researchers. They were able to work closely with research leaders with much greater experience navigating within and through the research sector. It provided a supportive environment within which an early career researcher could contribute or even lead a working group. Feedback from online surveys (Weber et al., 2013) showed that other members of the group mentored early career researchers through the process, providing invaluable learning experience on managing large research projects with a range of intellectual inputs. This opportunity can lead to more confidence to network with other experts, which in turn stimulates further collaboration.

2.4. Enhanced transdisciplinarity

A key benefit of syntheses centres arises from their challenge to participants to contemplate alternative perspectives and different degrees of 'proof'. They can greatly assist in modifying the behaviour and broadening the thinking of participants necessary to develop workable synthetic solutions to multi-faceted problems. Participants are exposed to philosophical differences between disciplines and as a result are better positioned to embark on improved transdisciplinary research in the future.

Policy and environmental management practitioners were encouraged to participate in ACEAS working groups. One Assistant Director with a national environmental agency stated that his involvement in two working groups reinforced his understanding of the need for, and value of inclusion of, a full range of stakeholders in environmental problem solving (ACEAS e-newsletter June 2013).[12]

Engaging managers within the synthesis process aids in realistic problem conceptualisation and the development of applied research of practical, contemporary benefit. Researchers can recalibrate their research priorities to those of genuine utility to managers and policy-makers rather than being those that the researcher believes should be of importance to the managers.

Outputs from synthesis have the potential to engage managers and policy-makers by distilling 'global' knowledge to provide regional insight, eventually to local decision-making and action. There is also enhanced potential for more rapid uptake of newly synthesised information into management and monitoring. Furthermore, it enables greater familiarisation for data custodians of the data collection process, thereby mitigating a key risk associated with 'big' data, that is, misinterpretation and misuse due to poor understanding of data limitations.

2.5. Enhanced theoretical and analytical understanding

The process of synthesis often begins with defining a problem or knowledge gap that is best addressed across multiple domains. The participants in a synthesis group may hold established notions concerning elements of the problem, but have limited clarity on how their understanding plays out in the larger system. They also may have limited

9 http://www.aceas.org.au/newsletters/june2013/ACEAS-June13.html.

10 http://www.aceas.org.au/newsletters/dec2013/aceas-dec13.html.

11 http://www.aceas.org.au/newsletters/ACEAS-December.html.

12 http://www.aceas.org.au/newsletters/june2013/ACEAS-June13.html.

awareness of some relevant research due to the exponential growth in publication outputs. The working group can advance knowledge by exchanging information, exploring new techniques, developing conceptual models and analysing the models using meta-analyses. Integrating information and data from different sources results in a more holistic understanding of a problem than would be possible without the synthesis group, especially when data are drawn from many studies that add up to a continental perspective.

Two illustrations of this come from the ACEAS Pyrogeography working group and the northern quoll (*Dasyurus hallucatus*) demography working group. Contrary to proposed conceptual models of primary productivity and fire frequency as the primary drivers of fire regimes, the Pyrogeography group found that changes in summer monsoon rainfall activity in Australia were crucial (Murphy et al., 2013). Their new framework could be developed as a mapping tool for vegetation management, and for dynamic global vegetation models. Although the northern quoll (*D. hallucatus*) is not listed as threatened in Queensland, demographic modelling of this medium-sized, carnivorous marsupial by the ACEAS-sponsored 'northern quoll demography group' has shown that the species is faring no better in that state than in the two other states in which it occurs (Western Australia, Northern Territory), where it is listed as endangered. In the latter states, the species has declined by more than half in the past ten years in areas invaded by cane toads (*Rhinella marinus* syn. *Bufo marinus*). In Queensland, initial declines occurred two to four decades ago after the invasion of cane toads, but other processes affecting these small populations (possibly invasive predators such as feral cats, and perhaps habitat degradation in the more urbanised, less rugged parts of the state) have prevented recovery (D. Fisher et al., unpubl. data).

Pennington (2011), reporting on the operation of successful interdisciplinary teams, noted that participants consistently observed that the most compelling outcome is the intellectual stimulation and creativity generated by the collective group. For almost all professionals, there is always the danger of developing rigid modes of thought or practice arising from working with people of similar backgrounds and responsibilities. Working in transdisciplinary groups, especially ones with social scientists specialising on environmental problems, can help to 'educate' scientists about the contributory rather than predominant role that scientific knowledge plays in policy and management. Similarly, social scientists learn about the degrees to which scientists rely on empirical evidence to make statements about problems, and their reasoning for doing so.

2.6. Stimulation of conceptual advances

Synthesis centres contribute to conceptual advances in two main ways: (1) the construction of models that synthesise expert knowledge and data relevant to a problem; and (2) meta-analyses. These approaches capitalise on the gathering together of specialists with deep knowledge about a topic but who may have developed their individual thinking in relative isolation. The interactions among specialists constructively challenge individuals' thinking and often lead to 'show me the evidence' discussions about deeply held convictions.

The construction of synthetic conceptual models is a comparatively straightforward to-and-from dialogue among participants. The method often uses 'horrendograms', with many boxes and arrows on whiteboards, along with spirited debate about the merits of connections between mooted causes-and-effects, and the level of complexity needed to capture the salient dynamics of the system while achieving the requisite simplicity for a useful, comprehensible model. A second phase ideally follows in which the model is iteratively tested with data and modified to increase its explanatory capacity. Sometimes, the analysis phase identifies relationships that were not formerly apparent to the participants.

One ACEAS example of the construction of a conceptual model was by the 'Avifaunal Disarray from a Single Despotic Species' working group. The problem being addressed was the substantial changes in bird assemblages caused when the hyper-aggressive native Australian bird, the Noisy Miner (*Manorina melanocephala*), reaches a certain density. Reports from across eastern Australia noted such problematic increases in density, but there were different perspectives about the causes and consequent cascading effects. The working group developed models on both aspects and their underlying justifications (Maron et al., 2013), collated as much data as possible from across eastern Australia (Thomson et al., 2015), and is developing a third paper on evidence-based management responses.

A similar example of model building for management purposes relates to a NCEAS team which sought to determine the reasons for the decline of pelagic fish in the San Francisco estuary in California, USA (Mac Nally et al., 2010). Due to its importance to water management in that state, the model-building phase took more than four intense days to elicit an agreed model among the more than a dozen experts involved.

For these reasons, synthesis through meta-analyses is an important method to advance ecological understanding, despite some limits to their use (e.g. Whittaker, 2010). Rather than expecting a process to hold everywhere or not at all, a better question is: how often does that process hold and under what circumstances? If the process being examined is frequently observed (e.g. in >50% of studies), then it is likely to be an ecologically important phenomenon. A good example was the evaluation of evidence for Connell's (1978) intermediate disturbance hypothesis, which posited a hump-shaped pattern of species richness or diversity as a function of increasing physical harshness of the environment. While an intuitively appealing idea, an evaluation of about 200 studies provided little support for such a relationship (Mackey and Currie, 2001), indicating the need to explore other influences on diversity patterns.

Synthesis centres are ideal venues to piece together the various components needed to undertake meta-analyses. The phases are: (1) a precise statement of the issue, (2) clarification of terminology, (3) specification of search terms to scour published and 'grey' literature, (4) development of scoring approaches, and (5) identification of statistical methods to analyse the extracted information. The bigger and more critical the question, the more important it is to work through these issues at the beginning.

A case in point is the meta-analysis approach of the ACEAS working group 'A Cup Half Full? Thresholds and Regime Shifts in Australian Freshwater Ecosystems'. The group's initial stance was acceptance that there are regime shifts in freshwater systems associated with anthropogenic or natural pressures, leading to 'alternative stable states'. However, group discussions led to a call to evaluate whether there was strong evidence for such alternative stable states. This is an important issue because ideas from the alternative stable states literature have encroached into environmental management thinking more generally. By reviewing the context, methods, ecological, pressure and change characteristics reported in each published study in relation to the theoretical constructs of regime shifts, the meta-analysis showed that there was limited evidence for the assertion of regime shifts apart from in shallow, permanent lakes (Capon et al., 2015–in this issue). The process of using meta-analysis to question ideas that are often taken somewhat blithely led to one member of the 'A Cup Half Full' group to engage in an analogous meta-analysis at NCEAS, on the evidence for pressure-induced shifts in estuaries and near-shore ecosystems. Similarly, there was virtually no compelling evidence for state changes associated unequivocally with pressures, largely because time series of ecological state and pressures are very rare (Mac Nally et al., 2014). Thus, these synthesis centre working groups have established relatively conclusively that there is little evidence for thresholds and alternative stable states in freshwater, brackish and near-shore aquatic ecosystems.

2.7. Stimulation of methodological advances

Routine feedback showed that provision of time, dedicated space for brainstorming, and a common purpose enabled the development of novel solutions and breakthroughs, and stimulated methodological advances to complex problems (Weber et al., 2013). The ACEAS working group 'Finding our way: the sharing and reuse of animal telemetry data' exemplifies this outcome. After finding that about half of animal telemetry studies were not published in the scientific literature, the group (Campbell et al., 2015–in this issue) implemented a case study to 'mine' such datasets. By supplementing open-access animal telemetry research metadata with additional information from data custodians, and integrating it with environmental data, they produced probability maps of feral cat distribution. The outputs of their study will be used in feral cat control and native mammal conservation, and also helped develop best-practice methods for animal-telemetry data storage, discovery, access and analysis.

Similarly, the ACEAS 'SPEDDEXES' working group developed a new approach to working with very large datasets; an important issue given the ever increasing need for amplified data collation, access, management and analytical capacity. The group focused on the key issues of facilitating standardised archiving protocols and methods, and developing open source code and tools for enabling data archiving and access (http://speddexes.tern.org.au/). The challenge of working with large, heterogeneous datasets, and knowledge gained through the analysis and synthesis process is discussed by Specht et al. (2015–in this issue).

Methodological advances were also made in policy-making. One group of molecular biologists, spatial analysts, policy-makers, conservation scientists and managers was brought together in 2012 to consider how to include phylogenetic measures in conservation policy and guidelines (Laity et al., 2015–in this issue). Until this meeting, conservation decision-making included genetic but not phylogenetic data, despite recent advances in phylogenetic information. Another group of agency policy-makers and researchers met to discuss the application of the IUCN Red List Criteria risk assessment framework in Australia. This group used spatially explicit stochastic population and dynamic species distribution models projected for future climates to determine how long before extinction a species would become eligible for listing as threatened based on the Red List criteria (Keith et al., 2014). The results of both working groups have been incorporated into government protocols.

2.8. Multi-forum communication of outputs

2.8.1. Communication products, forums and reach

The outputs from the ACEAS transdisciplinary synthesis working groups were communicated through a variety of forums to other scientists and managers, as well as policy-makers, students and the general public. Along with peer-reviewed papers, conference posters and published reports, online data repository services were used to enable anyone with Internet access to examine spatially explicit, interactive products relevant for addressing real-world problems (e.g. aerobiology studies, animal telemetry, Indigenous bio-cultural knowledge). Press releases attracted local, national and global audiences. Websites conveyed information about the organisation and research to the public[13] and each working group,[14] while social media (Twitter,[15] Facebook,[16] YouTube[17]) were used to portray live discussion groups (i.e. a dramatised Hypothetical[16]) and to post updates on activities, synthesis products and unique outputs.

An example of such a product is the 'Blue Carbon Blues' song. Developed by the Seagrass working group (Kilminster et al., 2015–in this issue), this song has been used to educate the public, and in interactions with secondary and undergraduate students.[18] One year after posting, the YouTube clip had been viewed 2598 times. Another example is the inclusion in a business management and IT commerce textbook of a feature on the use of remote sensors to monitor systems or individuals, and the wireless transmission of these data (Gray et al., 2015, pp. 356–7). The case study illustrated the wider potential of telemetry in the modern world, beyond the development of medical equipment, car manufacturing and phone apps such as 'find my phone', but also the challenges of data management, analysis, synthesis and publication (Dwyer et al., 2015; Campbell et al., 2015–in this issue). Exposure through such alternative outlets extends the reach of research to a diverse community and provides rich, high value resources for education, decision-making and business.

2.8.2. Value of the products for education

Primary data and synthesised information available through online products (e.g. the TERN Data Portal[19]) provide an authoritative source of quality information. Synthesised products enable easier access for education and research, at a much faster rate than would have been achieved previously (e.g. primary literature, textbooks, direct contact). They facilitate problem awareness, more efficient, accurate, and repeatable science, and aid in developing narratives about real-world problems. The increased communication of research outcomes through press releases and social media helps raise public awareness, generate interest, promote decisions, and raise funds. Increased access enables scientists and managers to identify prior research, relevant contacts, current knowledge gaps and research needs. To be sustainable, this aggregation of data needs to be consistent, searchable and transparent, with appropriate metadata to enhance data discovery and catalogue searches (Section 2.1), and to promote inter-operability between past and future data collections.

2.8.3. Value of the products for management

Synthesised information, conceptual models, and collated spatial and temporal products aid communication with stakeholders and provide a framework for discussions about policy, management and monitoring programmes. ACEAS working groups have contributed to management through targeted communication of the vulnerability of aquatic ecosystems (Crook et al., 2015–in this issue; Davis et al., 2015–in this issue), the response of vegetated landscape to land use change (Thackway and Specht, 2015–in this issue), the responses of different Australian ecosystems and plant species to fire (Clarke et al., 2015–in this issue), and the management requirements for seagrass (Kilminster et al., 2015–in this issue).

Environmental managers commonly use monitoring data to assess water supply and quality, detect disturbance, track landscape connectivity, and to assist development of regional-to national-scale management plans. For example, access to data on the spatial arrangement of resources (e.g. seagrass), species distributions (e.g. northern quoll distributions), and habitat connectivity (e.g. telemetry data, aquatic connectivity) is extremely valuable for developing recommendations about site management (e.g. developments, transport infrastructure) and conservation planning. Larger-scale analyses not only show the spatial arrangement of resources but highlight the data and knowledge gaps (e.g. Indigenous bio-cultural knowledge), enabling development of strategies for targeted, cost-efficient data acquisition.

The ACEAS model of including policy-makers, managers and practitioners in working groups proved invaluable in accessing corporate knowledge and experience not always published or available to scientific researchers. These scientists and practitioners working within government agencies and non-research organisations would probably

[13] See http://www.aceas.org.au/.
[14] E.g. http://www.aceastern.wikispaces.net/.
[15] See https://twitter.com/ACEAS_Aus.
[16] See https://www.facebook.com/aceastern?fref=nf.
[17] E.g. http://www.youtube.com/watch?v=phwvYoBi8DQ, http://www.youtube.com/watch?v=gw6HDOI5WSw, http://www.youtube.com/watch?v=bZ8XZA8QAP4.
[18] See https://www.youtube.com/watch?v=U8KOOd9uzTE.
[19] See http://aceas-data.science.uq.edu.au/portal/.

find it difficult to generate such synthesis activity within their own organisations. Even if they could, the focus would more likely be regional to state-wide rather than national to international or bigger picture fundamental problems.

2.9. Transforming scientific narratives into community dialogues: the socio-ecological imperative

Ecological synthesis centres create opportunities and mechanisms to inform and engage the community and policy-makers on significant issues of public interest. However, many scientists have limited experience in translating, communicating, and debating complex and nuanced concepts as they apply in broader societal contexts. There is nevertheless an urgent imperative for ecologists to develop narratives that resonate with and stimulate public discussion. Synthesis can assist societal implementation of ecological advances through an illustrative, narrative role. Creation of a narrative that touches the audience (logically, emotionally, morally) is vital to effective communication. The audience here is primarily policy-makers (i.e. public servants, legislators, politicians) and resource managers (e.g. farmers, graziers, miners, government officials). Some examples from ACEAS working groups include the following.

The working group on 'transformational change of regional landscapes' identified a series of significant events that shaped Australian land use (Bryan et al., 2013). They specified that there is a need to communicate about 'safe working limits' in agro-economic utilisation of the environment, and a need for decentralised, devolved decision-making (based on a synthesised view) at a regional level. Their synthesis identified that there is insufficient bottom-up engagement and divergent perspectives on environmental sustainability: from deep green conservation beliefs that 'safe utilisation' is an anathema to agriculturalist views that the only limits to utilisation are economic limits.

Davis et al. (2015–in this issue) assessed the intensification of hydrological cycles and agronomic effort globally. They highlighted the vulnerability of water-dependent ecosystems to climate change and the need to develop a long-term understanding of aquatic ecosystem behaviour.

The Finlayson-led working group analysed adaptation pathways (e.g. dispersal, life history) for aquatic plants under climate change and ecosystem fragmentation.[20] They identified the responses and sensitivity of wetland plants to these processes, which could assist in better wetland management in a drying climate. Their secondary product (a database on aquatic plant distribution) could be used to create a narrative about species rarity, endemism and dependency, and would appeal to a variety of audiences.

2.10. Embracing feedback and evaluation

Synthesis centres undertake a variety of routine monitoring and evaluation activities, as well as specific evaluation studies. For example, NIMBioS was the subject of a PhD project investigating the publication and collaboration behaviours of participants (Bishop, 2012; Bishop et al., 2014), while NCEAS feedback was evaluated by Hackett et al. (2008).

As the ability of participants to collaborate was anticipated to be a core component of success, a survey of the readiness of the stakeholder community to collaborate and share data was conducted (Keniger and Specht, 2012). Of the 721 responses received from members of the ecosystem science and management community, a large complement thought that interdisciplinary collaboration was important, but there was little evidence provided of active collaboration beyond the respondent's close disciplinary colleagues. Some of the results of this survey are discussed in Specht et al. (2015–in this issue).

ACEAS undertook comprehensive self-evaluation activities to ensure effective monitoring and reporting of performance. This primarily involved feedback surveys after workshops, but also was informed by ACEAS staff diaries, de-briefings, and verbal feedback from participants to staff. The surveys assessed participant satisfaction, group dynamics and performance, attitudes to data sharing and collaboration, expected products and outcomes, and ways to improve ACEAS functioning. Questions were added in later surveys to assess working group diversity (i.e. gender, location, discipline) and achievement against the six ACEAS objectives.[21]

The survey responses stressed the importance of venue suitability (e.g. internet access, physical remoteness), good quality food and coffee, and 'face-to-face' dedicated meeting time. As noted by Hampton and Parker (2011, p. 901), face-to-face meetings in a neutral, remote location 'significantly increase the velocity at which ideas are generated'. It improves group dynamics by facilitating group bonding, promoting development of trust, commitment and communication efficiency, and removing distractions. This enables what has been described by Ylijoki and Mäntylä (2003) as 'timeless time', or the ability to transcend time through immersion in work by escaping external pressures and demands. Indeed, many working group participants commented in the ACEAS surveys and feedback how they valued the opportunity to focus on a single objective and task. Working group composition (i.e. discipline diversity, expertise, experience, geographic representation) and leadership (by the Principal Investigator and/or other participants) were also identified as strong influences on the achievement of working group goals.

Feedback led to adjustments in ACEAS procedures and better anticipation of participant needs. Clearer instructions were provided on use of the on-line collaboration tool, and the types of available support were broadened (e.g. support staff funding, part-funding of additional meetings). In addition, a mid-term review was undertaken by external consultants (Price and Cork, 2013) and a socio-economic analysis of ACEAS was conducted (RMCG, 2014). It is notable from these studies that co-investment was significant; conservative figures showed that for every dollar invested by ACEAS, the participants and their organisations invested at least $1.70.

3. Conclusions

The drivers for syntheses can come from many sources, both formal and informal. While syntheses do occur within and among disciplines and within the spheres of ecosystem science, policy and management, structured synthesis centres are making a valuable contribution. As illustrated herein, the benefits of synthesis and synthesis centres are numerous. Synthesised information and scientific data are highly valuable to environmental managers and policy-makers who often lack the resources, time, diversity of experience, or capacity to undertake the task themselves. Based on our experience with ACEAS, we advocate the transdisciplinary synthesis approach to systematically address complex environmental problems and synthesis centres as key to enabling the process. This task is most effectively conducted through participatory collaboration, in which managers and policy-makers guide the framing of the research questions in order to address current management needs and external stakeholder requirements. It is clear that investing in synthesis centres can deliver significant outcomes at a comparatively great benefit-to-cost ratio. We believe that the increasing trend towards big, synthetic science is advantaged and facilitated by the increasing number of synthesis centres (Fig. 1).

We perceive the barriers to synthesis as being primarily related to data access and sharing, and to the provision of longer term, core capacity. Data-related barriers generally are derived from concerns about appropriate data use, acknowledgment and reward, but also about data

[20] See http://www.aceas.org.au/Adaption_pathways_140502.pdf.

[21] See http://www.aceas.org.au/index.php?option=com_content&view=article&id=46&Itemid=117.

custodianship, metadata and availability. Synthesis centres can play a key role in managing these issues and overcoming barriers: by promoting the use and standards of metadata documentation, providing online data repository services and support, ensuring acknowledgement of intellectual property and sufficient time for production of research products, and by facilitating transdisciplinary synthesis working groups. It is notable that the act of sharing data was found in the ACEAS working groups to help reduce the fear of sharing and to promote the practice. The benefits of sharing are considerable; synthesis groups were able to conduct analyses at previously nearly impossible scales (Hampton and Parker, 2011), to inform policy, and to answer long-debated questions (e.g. Violle et al., 2015–in this issue).

In mid-2014, a national workshop was convened to reflect on the achievements of the ACEAS synthesis centre before it closed. Feedback at that workshop indicated very strong support for the tangible services and benefits provided by such a synthesis centre. These parallel the acknowledged value and outcomes of other international synthesis centres (Table 1). For example, in talking about NCEAS and NESCent in the United States, Rodrigo et al. (2013) asserted that innovative solutions to 'big picture' problems cannot be done by email but need real-time, face-to-face interactions, building of communities of practice, and logistical, administrative and informatics support; core functions of synthesis centres as 'science incubators'.

For those planning another Australian synthesis centre, we have gleaned the following from our experience and an analysis of successful, enduring, independent international synthesis centres. We propose that success is best enabled by:

- ☐ face-to-face meetings as a core function;
- ☐ immersion in 'timeless time' (Ylijoki and Mäntylä, 2003) working sessions;
- ☐ longevity of working groups with multiple working sessions to maintain research continuity and accelerate progress;
- ☐ collaborative opportunities between working groups (e.g. grand workshops);
- ☐ a separate strategic direction not explicitly tied to sponsoring or hosting agencies;
- ☐ a capacity to provide informatics and research support beyond face-to-face meetings;
- ☐ a capacity to provide support for remote engagement and novel product-delivery;
- ☐ a separate line of accountability regarding administration and reporting requirements from that of the sponsoring or hosting agency;
- ☐ a partnership model with key national universities;
- ☐ a high level national council or board representing the broad interests of the biophysical sciences providing quality assurance and equity; and
- ☐ support for, and researcher engagement with, leading influencers from science, policy and management sectors.

At a working group level, coordinated leadership, trust and effective communication are critical, as are issues of language, data relevance, methodological and analytical approaches, and communication of findings. It is important that the working group has an agreed, precise problem statement and objectives (i.e. a 'song sheet'), and that perspectives, language and terminology are explored and clarified at an early stage. The use of terms and definitions in published and unpublished realms may need to be evaluated and agreed to enable a common understanding. Criteria may need to be developed to identify data and information that are appropriate and adequate to address the key objectives of the working group. This may include scanning of who, what, where, when and how the data were collected and assessment of their fit for purpose (qualitative, quantitative or both). Data and information need to be evaluated to discern if they have serious flaws or gaps, have issues of licensing and access, or need to be transformed or normalised prior to use. The methodological and analytical approaches (e.g. scoring approaches, statistical methods) also need to be evaluated for their appropriateness given the available data, the working group and synthesis centre capability, and the time available for analysis. Sometimes, new data or information (possibly compiled through expert elicitation) may be needed to remove bias or provide a more representative, comprehensive or adequate solution. The research findings also need to be compiled and disseminated to appropriate forums and stakeholders, along with recommendations on how to improve the process and outcomes.

One of the key objectives of ACEAS and other synthesis centres is promotion (as appropriate and relevant) of the outcomes for use and implementation by science, policy and environmental managers. Yet, policy uptake of ecosystem science findings and recommendations is a recognised challenge (Ryder et al., 2010) with past implementation being primarily through habitat, species and reserve planning, or conceptual or long-term advances (Ormerod et al., 2002). Sustained support for synthesis centres along with increased involvement of policy-makers in working groups is needed to build the trust, knowledge and communication to address this challenge.

Lastly, continuity of synthesis centres as 'science incubators' is essential to fully reap their multitude of benefits. Long-term, sustained support is essential because, as argued by Rodrigo et al. (2013 p. 1), 'synthesis centers are actually places where innovation happens in ways that avoid the multiplication of resources and infrastructure that are funded through capital and indirect costs on individual grants.' In Australia, research for conservation and ecological management is mostly funded through nationally competitive grant schemes on discipline-specific projects. The relatively modest spending on synthesis has been a valued investment in integrating scientific knowledge with policy and management expertise. Synergies between established grant schemes and synthesis groups have also emerged through learning and ideation about important knowledge gaps that can be developed for research funding schemes or further working groups. For example, members of two ACEAS working groups successfully initiated further working groups, while there have been 11 Australian Research Council grants awarded (totalling $5.56 million) to which ACEAS has contributed in part to their formation and success.

We conclude that transdisciplinary, trans-organisational innovation is most efficiently and effectively enabled through the support of synthesis centres and the research-practice engagement and networks that they advance. Synthesis is complementary to other ways of doing science (observation/experiments/modelling). By developing, communicating and promoting the use of synthetic transdisciplinary research, synthesis increases the generality and applicability of scientific research (Hampton and Parker, 2011). Synthesis centres are the necessary scientific infrastructure to achieve all of this.

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