Science Through a Big Window

Presidential Address 2020

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It has been a strange and difficult year of ongoing drought, fire, flood, pandemic and economic disruption – a year where the tools of the digital age have become more essential for the continuity of scientific research, communication and education. What can we learn from our 2020 experience? *Business as usual will not solve our present and emerging human and biosphere-related problems!*

Life System Interconnectedness

One underlying reality has become increasingly clear, i.e. the interconnectedness of life systems. Never in recent times have ecological relationships for our species and associated biodiversity within ecosystems at a global scale been so powerfully exposed under the impact of climate change. This existential emergency is expressed as increasing intensities of fire, flood and accelerating ecosystem degradation with increasing pollution, in parallel with the ongoing realities of zoonosis, in the pandemic COVID-19.

The condition of the world's ecosystems has moved a long way from Sir Arthur Tansley's (1935) perceptions of the then conservation status of vegetation systems within his experience (Tansley (Ed.), 1911). Notwithstanding this, his initial broad definition of ecosystem is still relevant and applicable today. Paraphrased, the term 'ecosystem' was coined to recognise the integration of the biotic community and its physical environment as a fundamental unit of ecology – within a hierarchy of physical systems from atom to the universe.

So much change has occurred over most of the biosphere since 1935 that we are now dealing with what some researchers call 'novel ecosystems' (Hobbs et al., 2006). Irrevocable decisions by government and landholders have created 'novel ecosystems' that have changed the nature of land management problems and our economic and environmental capacity to contribute to theory-based models to underpin sustainable on-ground practices (UN Report, 2018). The original values have been modified, destroyed or coalesced with invasive species, complicated by waves of land degradation, which are ever increasingly influenced by the vagaries and intensifications of climate change (Hobbs et al., 2006). It also needs to be recognised that prior to 1788, it is unlikely that any ecosystems in Australia were not influenced in some way by Indigenous cultures (particularly by fire) over the previous 60,000 years or so. During the last 240 years, our complex society has not in general been modifying a pristine wilderness, although the landscape certainly contained and continues to have locations of high wilderness value.

In recent times, at least four approaches to ecosystem science can be identified:

1. *Biologically centred*. This approach considers the 'organism' as the focus of study within an ecosystem.
2. *Process-oriented*. This approach views the ecosystem as a set of processes, focusing mainly on the flow of energy and matter.
3. *Geographical*. A geographic space that recognises the ecosystem unit as an area of sufficiently similar topography, climate and biology (Blew, 1996).
4. *Heuristic*. An ecosystem is really no more than a conceptual device (MacFadyen, 1975).

Conceptually, there may also be hybrid versions of the above. In this address I use the basic concept of Tansley (1935) that, as a starting point, "an ecosystem, is the complex of living organisms, their physical environment, and all their interrelationships in a particular unit of space" (Encyclopaedia Britannica, 2020).

It is little wonder that developing a relevant theory of ecosystem science has remained problematic. There are serious limitations regarding the present underlying theoretical base. The challenge of rigorously understanding information flow and linkage between different levels of scale remains a persistent problem. There is no unified theory of ecology. *We cannot predict the production of wheat in a wheat field by measuring the electron transfer on the surface of a granum in a chloroplast of a wheat leaf!* This is my usual example, when seeking to explain that the 'scale distance' between levels can often place many predictions in an absurd position. Rather than becoming the mainstream challenge for ecology, ecological research has for many decades focused on those who seek to expand knowledge by deep understanding at the micro (biochemical/physiological) end of the spectrum and those who seek to place investigations in a geographic-landscape context.

Notwithstanding this, we can seek to identify emergent properties that can assist in linkage between levels of scale. Further, we now have tools that can significantly assist those researchers involved, e.g. supercomputers, parallel processing, integrative analysis protocols and next-generation algorithms – in conjunction with multiple inputs from big data (including remotely sensed), more powerful error rectification and reconciliation methods between datasets, and rigorously described and validated metadata that define the limits of dataset use, et cetera.

We need to use these tools. Nevertheless, and understandably, most scientists appear more comfortable when working at more manageable scales and largely employing traditional hypothesis-testing approaches. Their papers can be more readily published. That is how, at present, they mainly get recognition and satisfy their terms of employment.

A 'business as usual' approach in scientific research will not solve our current 'big' problems, e.g. global warming, sustainable energy to drive human societies, COVID-19 and the inevitable onset of further zoonotic impacts. However, in the current era, solutions to whole-system problems usually remain unsolved – until we, as a super-generalist species, face a crisis. History tells us that our ability as a species to foresee a crisis and take timely evasive action is also very limited. Perhaps the best example of that is the fact that at least 40 years have passed since prescient scientists began to warn of impending anthropogenic-affected climate change and other serious problems related to pollution and loss of biodiversity. In the future, with the coalescence of global drivers in relation to environmental, social, cultural and economic conservatism, we are likely to rapidly reach thresholds – ecological tipping points when crisis responses will not meet the challenge. As the Global 2000 Report makes clear (Speth, 1980), previously we needed to act much earlier, but regarding the big problems it has become crucial that we act seriously, intelligently and urgently – now! That was forty years ago!

Developing a Personal Wide-window Approach to Ecological Science

To explore some of the challenges involved, I will briefly refer to a few of the investigations I have previously conducted or led and some of their outcomes. These projects address steps towards wide-window understandings as elements in a whole-systems approach to ecological science.

First, let us revisit some basic principles of systems science:

- A system can be any scale. This could range from a leaf if we are investigating, say, fungal impacts on specific plants, to the Earth if we are considering global climate change. Thus, the level of focus needs to be clearly defined.
- In hierarchy theory relevant to systems research, three levels of importance are usually recognised: the level of observation; the level below – which influences or explains what happens at the level of observation; and the level above – which is influenced by the changes that occur at the level of observation (Hynes & Scanlan, 1993).

Systems scientists look for general principles that can apply across both natural and social sciences. They support the position that reductionist methods cannot produce a comprehensive understanding of 'organised' complex systems (Barlow, 1992). Methods include multidisciplinary and cross-scale research strategies.

Let me place in context my approach to wide-window ecological science and how it has evolved over the past 50 years. An address is not intended to be a book, so I have selectively and briefly followed the development and application of four conceptual frameworks. These comprise: *multi-level ecological analysis*; *preliminary conservation zoning for areas of high biodiversity*; and as complementary conceptual and analytical strategies, a brief acknowledgement of *conservation potential in forests and woodlands* and *the regeneration niche and the establishment niche of plants*.

Multi-level Ecological Analysis (M-LEA)

This includes ecological analyses that have employed frameworks that included GISs (geographic information systems) and IMSs (information management systems), numerical classification and ordination of data inputs – refined and distilled by sets of scientific filters.

The rationale of my study of the ecology of the *Nothofagus* forests in Central New Guinea (Hynes, 1973; Hynes, 1974a) created debate among supervisors and examiners as to whether I should even be allowed to proceed with this approach.[1] This incorporated 10 representative sites across the Central Highlands of New Guinea (ranging from 945 m–2682 m above mean sea level), focusing down to two major sites with nested studies investigating their environments and biotic communities and population cohorts of Antarctic beech (*Nothofagus* spp.) and associated species extant in these ecosystems. The Webb (1970) Rainforest Pro Forma was used when surveying structural and physiognomic characteristics on all sites (Hynes, 1974b). The studies also included soil and plant litter analyses and relevant plant physiological investigations. Detailed floristic and forest structural investigations (trees and saplings) were conducted on random stratified grids in two intensive sample plots on each of the major sites on Mt Giluwe and Mt Michael. Seedling studies and gap analyses were also conducted. This was the first detailed ecological study of these forests in Papua New Guinea (Johns et al., 2007).

Notably, the International Biological Program (IBP 1964–1974) introduced as one of the then main 'new technologies' a *systems-based approach* to global biological and related environmental investigations (Specht & Specht, 2020). The approach taken for my New Guinea Nothofagus Forests study was a preliminary application of this 'new technology'.

A more comprehensive framework was implemented in my work on the ecology and conservation potential of remnant woodlands in the Northern Pennines of England (Hynes, 1978a)[2]. This work comprised a multi-level ecological analysis of mixed deciduous woodlands. Investigations ranged from woodland surveys to analyses of tree increment (girth at 4.5 m) in the sampled woodlands and seedling growth on five sites over an altitudinal range of 229 m (750 ft) to 823 m (2700 ft). Detailed soil investigations (5 woodlands) were conducted, and climate data was continuously monitored at 305 m (1000 ft) on the major study site (Seedling Site 2). These investigations were complemented by tree seedling growth-cabinet investigations that simulated summer growing temperatures over the altitudinal range, which provided further insight. Multi-variate techniques, viz. numerical classification and ordination and traditional statistical methods were used to examine the database. Trees and seedlings of dominant species ash (*Fraxinus excelsior*), birch (*Betula pubescens*), sycamore (*Acer psuedoplatanus*) and rowan (*Sorbus aucuparia*) were used as biological indicators of ecosystem functioning throughout. Investigations of increasing intensity were conducted over the following levels:

- Zone II (elevated remnants) – 155 woodlands.
- Upper level survey – 18 woodlands.

[1] Page 89 summarises my approach at that time: "Ecological studies directed towards the biological community level by their very nature become holistic. The obvious criticism of this approach is that it attempts too much. This will always be partly true no matter how judicious a selection of areas for investigation is made. The justification submitted here for largely adopting this method in this work is itself ecological. For it is considered that only by seeking to come to grips with the problem by viewing it selectively in part and then as a whole, while acknowledging dangers inherent in such method, that a truly ecological perspective can be gained."

[2] Commonwealth Universities Scholar, University College London and the Department where Arthur Tansley first studied and taught.

- Tree vegetation (community structure/habitat studies) – 5 woodlands.
- Dendrometer investigations – 3 woodlands.
- Seedling studies – 3 in woodland and 2 above the tree line.
- Ecological synthesis investigations and a comprehensive statistical model – 1 woodland (major study site).

Multi-level analysis is an effective focusing, sorting and sieving mechanism for ecological studies that move though different levels of investigation, seeking meaningful linkages and understanding. A conceptual framework of M-LEA is presented in Figure 1.

When applied to investigate the need for a 'wide-window' framework to test research project relevance and likely effectiveness of outcomes in seven cases of weed research, three cases highlighted the need for wider research frameworks; the other four cases highlighted the need to identify key relationships between land use problems and comprehensive solutions. Both commentaries sit logically within the business of whole-systems science.

Figure 1. A simplified but graphical representation of the analytical processes employed in multi-level ecological analysis and the sequential stages though which it progresses. A detailed expansion of these stages is presented in Hynes (1978a), which also examines the theoretical challenges of connectedness between levels of scale and information links and flow. Logistically, the stages can be carried out in parallel during project implementation and integrated where and when research outcomes become available.

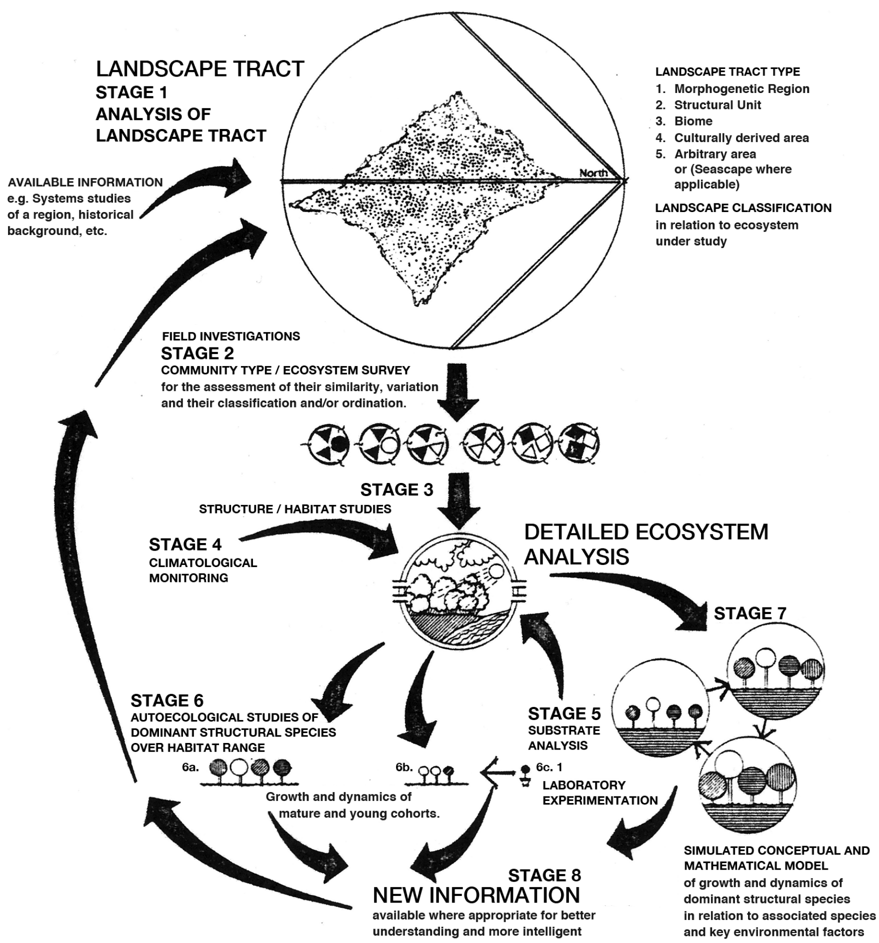
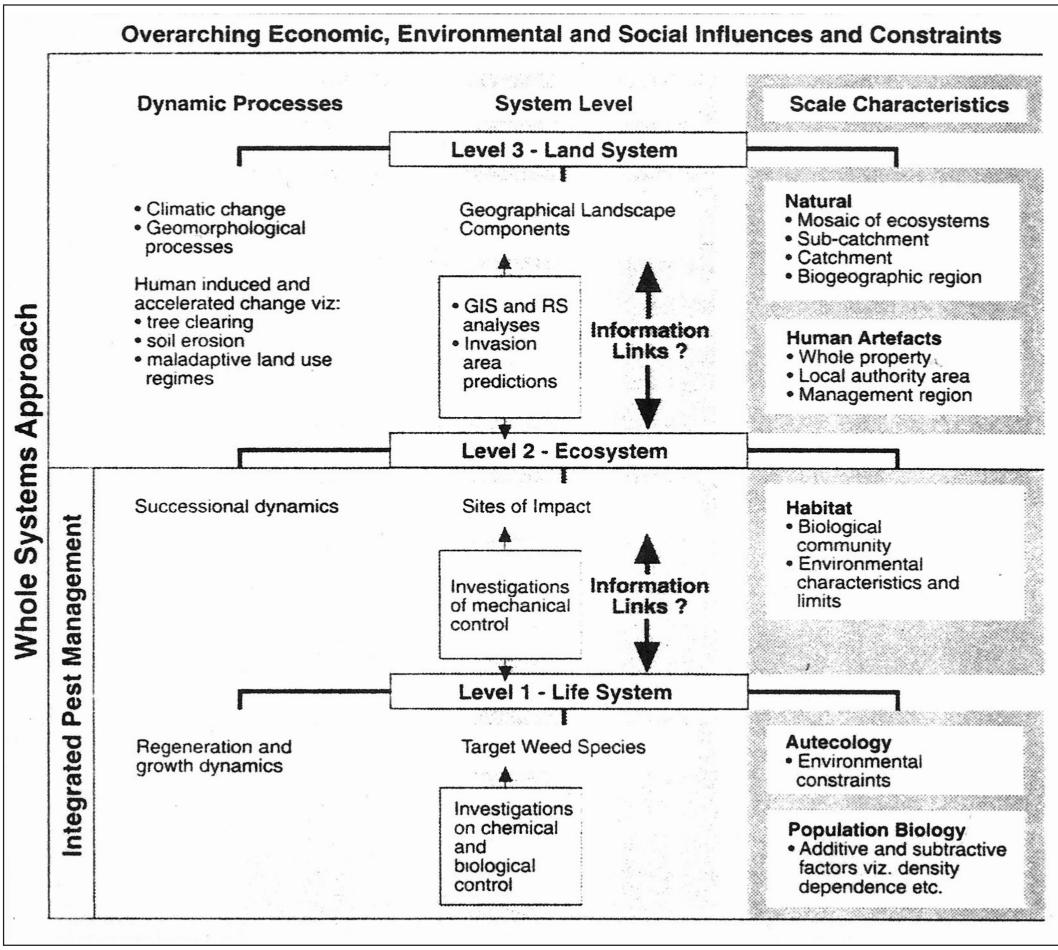


Figure 2. An operational framework for accommodating levels of organisational and physical scale in pest plant research. Systems modelling using computer protocols can be conducted at any level and used for linking information outcomes between levels. The framework can be used to test specific research investigations regarding whether or not they satisfy the implications of viewing the work through the wider framework provided by M-LEA or whether or not they need to identify key relationships between land use problems and comprehensive solutions (Hynes & Scanlan, 1993).



Preliminary Conservation Zoning in the Wet Tropics of Queensland

(a case study in conservation zoning for areas of high biodiversity)

The Wet Tropics of North Queensland is a region of high environmental and socio-economic complexity. In response to the challenge of land planning and management in the region, the Queensland Government established the Northern Rainforest Management Agency (NORMA) in 1987. I was appointed project leader and chair of the Scientific Advisory Committee.

A report on the work of NORMA (Hynes (Ed.), 1988) focused on scientific and technical matters related to the development of land resource zones. These zones were defined to be consistent with the essential themes of the World Conservation Strategy, the Australian National Conservation Strategy and the World Commission on Environment and Development report (1987), 'Our Common Future'.

The report had two major objectives:

1. To use data outputs from three parallel resource analyses in conjunction with the application of explicit scientific and management filters to produce an objective, strategic conservation zoning.
2. To draw conclusions and make recommendations pertaining to future sustainable multiple use of the resources in the region that were compatible with its nature conservation values; see Figure 3 (Hynes (Ed.), 1988; Goosem et al., 1989).

A graphic overview of the relationship between data sources and their analyses is presented in Figure 3.

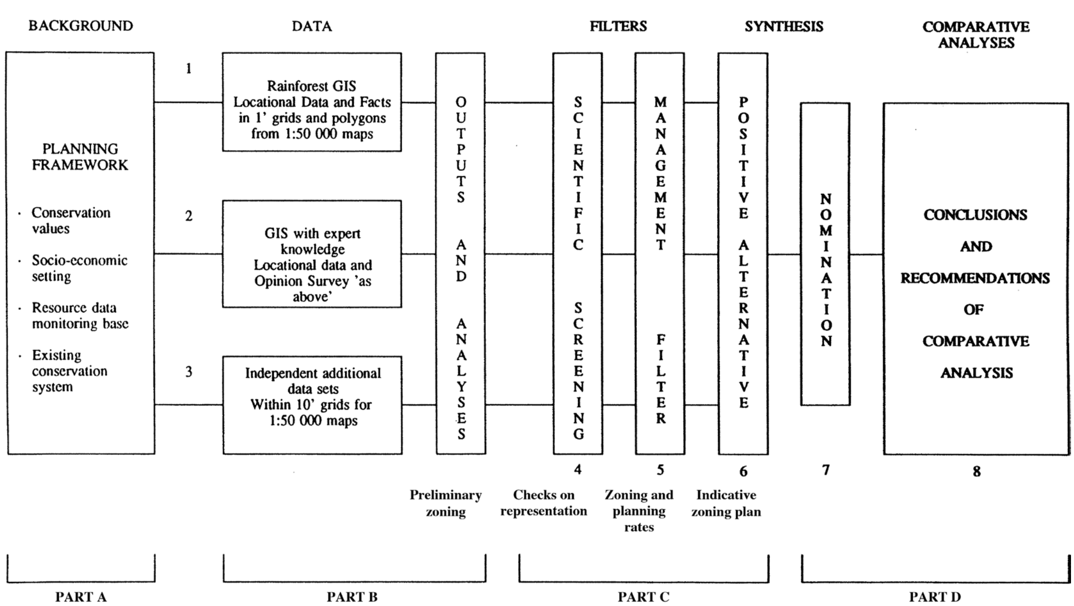
The report developed and applied concepts and approaches useful in identifying alternatives for decision makers in conservation planning. Several innovative methods were employed. One of the outcomes was an indicative dominant land-use suitability zoning map (Figure 4). This zoning approach best complied with the criteria for a Biosphere Reserve as described by the IUCN (1980). This work was a step on the way to a more comprehensive plan for the Wet Tropics.

This planning process under NORMA was superseded by the declaration of the Wet Tropics World Heritage Area (WHA) in 1989. Notwithstanding this, the GIS principles and issues involved are the same as those being adopted for the present WHA (Goosem et al., 1989). This work highlights the effectiveness of an analytical framework in managing multi-sourced data inputs and how the Queensland Wet Tropics GIS can produce, from its >350,000 species locations and other key information layers, valuable zoning outputs.

Complementary Frameworks Developed Over This Period

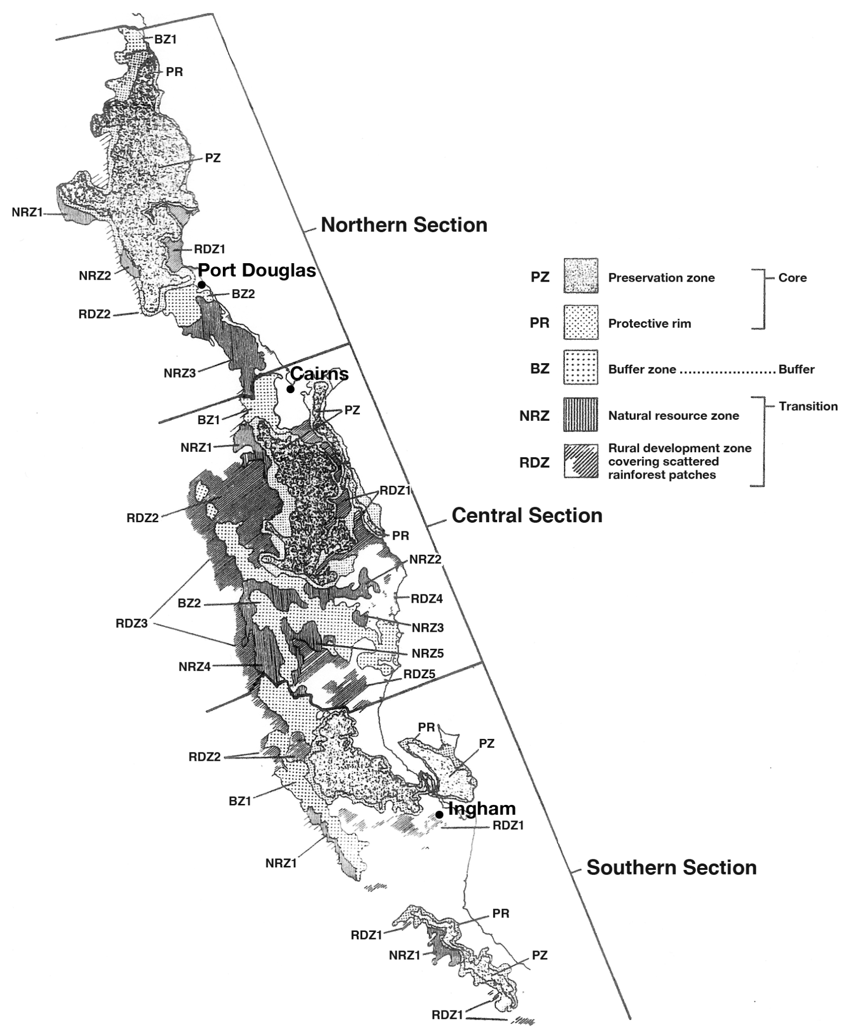
- *Comprehensive framework models of the establishment of tree seedlings, which encompass the regeneration niche and the establishment niche*. These frameworks were developed following the work of Harper (1977) and Grubb (1977) and have been applied and published in Hynes & Chase (1982), Hynes (1983), Hynes (1984) and Hynes (1989).

Figure 3. A flow diagram of the relationships between data sources and their analyses and the screening and integrating process involved in the NORMA project (Hynes (Ed.), 1988). This is an example of M-LEA applied to analysing large independent data sources as inputs to scientific screening and management filters in identifying options for conservation zoning in the Wet Tropics of North Queensland.



- *Conservation potential as a tool in vegetation restoration*. Conservation potential assesses the capacity of the landscape to return to its original condition through natural successional processes. This framework was developed in my woodland ecology project and continues to evolve over the years (Hynes, 1978a; Hynes, 1978b; Hynes, 1998; Hynes, in Davie & Ridwansyah, 2016).

Figure 4. Dominant land use suitability scenario-indicative zoning map of the Wet Tropics of Queensland. This presents an optimised preservation strategy with complementary conservation zones for multiple resource use. This synthesised output of the M-LEA approach, which provided an alternative land use and conservation scenario for the region (Hynes (Ed.), 1988) was superseded by the declaration of the WHA but provided an input to its initial planning. This indicative scenario is the computerised output of Stage 6 of the process outlined in Figure 3.



Zoning schematically presents the regional and sub-regional relationships between the zoning classes and resource use options. These classes define the dominant land uses in a zone. Other land uses can be present, but the controls and resource use prescriptions defined would be directly related to the nature of zoning class. Definition of land tenure types and refinement of cadastral boundaries make up the next stage in this process. Buffer zones, natural resource zones and rural development zones are numbered generally in a north–south order within sections.

These frameworks can complement M-LEA when applied as a part of the toolkit in investigating relevant components of whole-systems studies but are not explored further in this address.

Big Data and Whole-systems Science

In the foregoing cases the methods used were mainly employed prior to the evolution we are now experiencing in contemporary methodology for big data science. Notwithstanding this, they show how an individual's applied ecological research experience can strengthen awareness and help validate the application of multi-level and multidisciplinary frameworks in seeking understanding of the environmental problems that challenge us.

Ecology has recently seen rapid growth, driven mainly by advances in technology, greater access to big data and a growing awareness of the interconnections between humans and natural systems. As a discipline it has expanded beyond traditional themes and reductionist investigations to cover anthropogenic and contemporary data-rich, micro- and macro-scale themes. Increased availability of complex data, coupled with advances in technology and analytical capacities, has enabled this expansion from a classical theoretical discipline to a data-driven, multidisciplinary science that can apply knowledge to whole systems and their problems. Ecological research themes have shifted significantly over the past four decades (McCallan et al., 2019). (Notwithstanding this, we are still in dire need of a rigorous ecosystems-science theoretical base.)

The five key components of effective data management contributing to this expansion include measurable improvements in data quality, data access, data integration, data network and systems interoperability, and governance (Hynes, 2005). Hynes also elaborates on IT and information management tools, e.g. networks, distribution hubs, and, where relevant and essential, high-performance scientific computing. Information management systems (IMSs) need to be based on rigorously developed data models, and data inputs need to recognise data lifecycle constraints and the need to fill gaps with strategic data capture. The flow of data and information and data sharing between users, data generators and data custodians will be largely reliant on the quality of the interoperability of the IMSs involved (Hynes & Jones, 2004).

Paths to data access include: trawling and weaving; whole-systems approaches; and web-based access. Whereas the last two are usually essential for a whole-systems approach, they demand detailed descriptions. I will briefly comment on the first path here. A supportive path a user can follow when retrieving data is to apply a data-drilling, -trawling and -weaving approach. This can develop information summaries of similar information across many resources (databases). Here the concept of a 'data piece' is one way that information can be arranged that enables more efficient data integration (Gordon et al., 2003).

Big natural resource data analyses are not new to Australia or Queensland. Nevertheless, we have had a tendency to lose continuity and purpose because political decisions have often closed down statutory bodies responsible for crucial data management (Marlow, 2020). These bodies include: The Resource Assessment Commission (RAC, 1989–1993); the National Land and Water Resources Audit (NLWRA, 1997–2008); and the Queensland Regional Open Space System (ROSS, 1994–2012) (Marlow, 2020).

As a consequence, there remains a need for rigorous integration and perceptive, critical analyses of environmental big data at national and state levels. This deficiency currently limits the decisions we need to make in plotting the best pathways for sustainable management. It is more important than ever that we urgently rectify this situation to strengthen our chances of successful medium- and longer-term environmental and social outcomes.

Here I briefly overview some data-capture, data-management and integration approaches that allow effective input to big data investigations. These include: NEON (the National Ecological Observatory Network) in the USA; QLDGLOBE (Globe Queensland); and a precursor expert subsystem, ENRII (Environment for Natural Resource Information Integration); and One Health (OH) for *Homo sapiens* and Other Species, another established big data and coordination system of note.

NEON

The National Ecological Observatory Network became fully operational across 81 locations

(47 terrestrial and 34 aquatic), from Alaska to Puerto Rico, in May 2019. This marks a significant step forward in the history of ecology and will provide a substantial investment ($US2.4 billion) in continental-scale ecology. Its construction and maintenance will extend over 30 years (Balch et al., 2020). It is predicted that NEON will precipitate the next big shift in the discipline. Already, early adopters have produced over 80 broad-scale publications using NEON assets and 22,000 data downloads in the past two years.

Two major challenges have emerged. The first is to *build the core skills* necessary for open data-intensive ecology. An open data approach from the outset is a transformational element; however, essential skills are needed, and these include:

- best practices for developing and sharing – data, code, software, and entire scientific flows;
- comprehensive analyses of vast quantities of data on distributed cyberinfrastructure or the cloud; and
- collaboration skills in an open science framework that facilitate large-team science (Balch et al., 2020).

The second is to link NEON to major existing environmental datasets. There are at least four major additional environmental data sources that need to be harmonised with NEON. These include:

- existing observatory networks;
- emergent observing sensors and platforms, e.g. satellite systems such as Landsat and its derivatives;
- climate and land-use data; and
- derived simulation models.

Alone, NEON is powerful; combined with other data sources, it will be transformational.

Unique to NEON within ecology is its highly centralised infrastructure, management and data services. Despite its widespread footprint, all design and priorities flow from its headquarters (HQ) in Boulder, Colorado, and all data flow back for processing and posting to the HQ portal. Once posted, all data is freely available for download by anyone (SanClements & Thibault, 2019).

The vision is that the growing NEON science community will become the cornerstone of North American eco-science for the next three decades and address the continental-scale ecology questions it was designed to answer (Balch et al., 2020).

QLDGLOBE (Globe Queensland)

The Queensland Government and community stakeholders have had a dedicated interest in spatially defined natural resource data and its management for many decades (Hynes & Johnson (Eds.), 1989). Previously, this was held with associated datasets in data silos across a number of departments, usually specifically linked to their core business.

Globe Queensland was established in 2013–2014 (Jacoby, 2013, 2014). Built on Google Earth (GE), it provided an open portal to Queensland Government spatial and associated data in the GE format. It was replaced by a dedicated Globe Queensland system in 2017, along with several more specific data platforms such as QTopo, QImagery and MyMinesOnline. These platforms provide user-friendly, read-only services of hundreds of spatial datasets such as roads, property and land parcels, topography, mining and exploration, land valuation and natural resources (vegetation, water, soil, etc.). Other pathways for accessing many of the same datasets for independent spatial analyses, can be downloaded under prescribed copyright restrictions and various licensing arrangements via:

1. QSpatial (2020): http://qldspatial.information.qld.gov.au/catalogue/custom/index.page
2. Open Data Portal (2013): https://www.data.qld.gov.au/dataset

Whilst these datasets have became openly accessible to the community, each of the contributing government departments has retained their role as custodians of their datasets and the metadata describing them (Jacoby, 2013, 2014).

With changes of government came structural adjustments in agencies. Natural Resource Sciences, Indooroopilly were custodians of NR datasets during the 1990s and into the 2000s, and when the Dutton Park Ecosciences Precinct was completed and established in 2011, it became the repository for these datasets.

As manager of Natural Resource Information Management at the Natural Resource Sciences, Indooroopilly facility from 2000 to mid-2005, I was able to support a number of projects that contributed to the NR data silo. These projects, amongst others, included the development of the Soil And Land Information System (SALI): the first IMS to integrate ESRI spatial datasets with an object-oriented Oracle database (Clucas et al., 2002). We also, with seconded colleagues, developed the Environment for Natural Resource Information Integration (ENRII), which provided relevant standards, guidelines and protocols to achieve high-quality interpretation and integration across scales. Science in this framework can be integrated and linked to all-natural resource issues including those involving land, water, vegetation and climate. Through this tool, findings in one area can contribute to other natural resource understandings. The approach allows smart links, minimises duplication and provides pathways to improving management of natural resources across whole landscapes (Hynes, 2002; Hynes, 2004).

These projects were precursors to the current Globe and Ecosciences operating systems and platforms.

One Health for *Homo sapiens* and Other Species

One Health (OH) is a collaborative, multisectoral and transdisciplinary approach – working at local, regional, national and global levels – with the goal of achieving optimal health outcomes. It recognises the interconnections between people, animals, plants and their shared environment (Centers for Disease Control and Prevention (CDC, 2018; Alam & Chu, 2020).

Successful public health intervention requires the cooperation of human, animal and environmental health partners. Professionals in human health, animal health and environment and other areas of expertise need to communicate, collaborate on and coordinate activities. No one person, organisation or sector can address issues at the animal–human–environment interface alone.

OH is not new, but it has become more important in recent years and particularly at the present time with the devastating global impact of COVID-19. Many factors have changed the interactions between people, animals, plants and our environment in recent decades. Human populations are growing and continue to expand their geographic impacts. The Earth has experienced major physical and ecological changes, and this trend continues. The movement of people, animals and animal products has increased from international travel and trade. Diseases such as SARS, and presently COVID-19 (with SARS-CoV-2 being the causal virus), can now spread quickly across borders and globally (Centers for Disease Control and Prevention (CDC), 2018).

OH is a term that should not be used simply to describe obvious truths: that animals and humans can share diseases, or that environmental factors can influence the incidence of zoonoses. More importantly, it should galvanise us to look at ways to optimise clever upstream solutions to mitigate adverse health impacts (Salkeld, 2020). COVID-19 has laid bare the inadequacies in many societies and highlighted the injustices in minority groups worldwide.

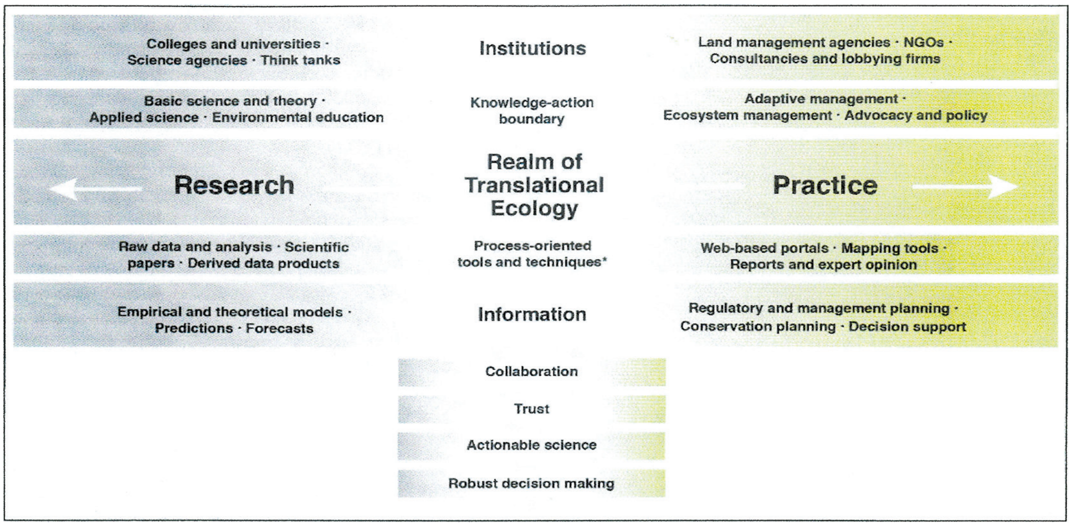
The year 2020 should be the start of a One Health global initiative, where social change, health and the environment begin to emerge as critical guiding lights for our global decision makers (Salkeld, 2020). OH epitomises a whole-systems approach, but perhaps would gain from a stronger and more versatile data management platform.

Professionally operated, big data management can effectively give *access to the right information at the right time for whole-systems-oriented solutions*. This capacity needs to be maximised in all three of the above network platforms and similar platforms to enable the efficient and relevant flow of information into research and community-linked methods that contribute to practicable sustainable outcomes.

Translational Ecology

Translational ecology is an emerging contemporary method that employs encompassing research strategies that can facilitate sustainable solutions and optimise inputs from professionally managed big data. “Translational ecology (TE) is an approach in which ecologists, stakeholders and decision makers work together to develop research that addresses the sociological, ecological and political contexts of an environmental problem” (Enquist et al., 2017). A TE strategy encapsulates an extended commitment to real-world outcomes. Effective TE increases the likelihood that ecological science will improve the decision making for environmental management and conservation (Enquist et al., 2017). The socio-ecological realm within which translational ecology operates is introduced in Figure 5.

Figure 5. The realm of translational ecology (TE). This is the nexus where knowledge meets action. It is situated at the intersection of a broad spectrum of institutions and information pathways where scientists, practitioners and stakeholders work together to build trust and to develop ideas, products and outcomes that are accessible and actionable, shaped by all participating parties, and can be readily used in decision making, scenario planning, structured decision making, climate adaption planning and other frameworks (after Enquist et al., 2017). M-LEA could positively contribute to this nexus.



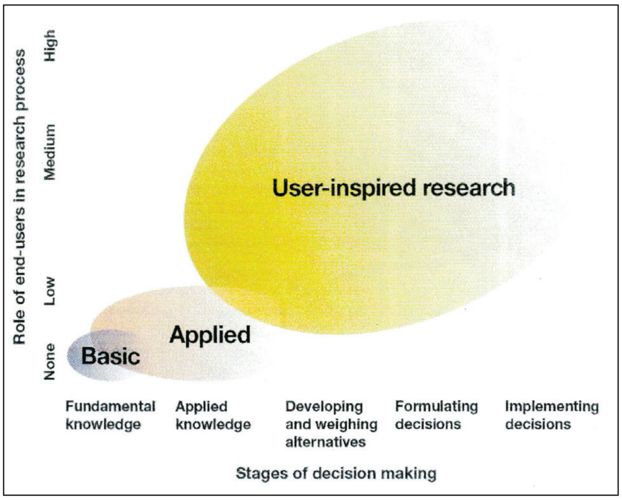
User-inspired TE can make research outcomes usable by and useful to decision makers (Wall et al., 2017). Barriers to the use of scientific information in decision making can be overcome by fostering social capital among collaborators, e.g. scientists, practitioners and members of the community. Relationships are fostered between groups through collaborative research opportunities, outreach and engagement activities. When participants openly acknowledge differences – in professional practices, expectations and rewards – a foundation for trust can be established. This is likely to increase the chances of successful collaboration. A well-articulated framework for managing engagement between ecologists, practitioners and other stakeholders increases the ability to identify mutually desired projects and assists in avoiding misunderstandings. Ecologists can avoid difficulties and improve the likelihood of effective scientist–stakeholder collaborative outcomes by consulting the body of successful case studies produced by science translators in ecology, public health and climate services (Wall et al., 2017).

The three research categories – basic, applied and user-inspired in relation to end-users and the types of decisions being made – are graphically represented in Figure 6.

Translational ecology must comprise more than clear speech, lexical equivalence and good intentions. To be effective, it requires understanding of the languages, cultures and currencies of policy, management and the societies in which relevant decisions are made. Translational ecologists need to understand the real-world contexts in which their science is applied; they must live simultaneously in two or more cultures. This is a field in ongoing development, but its perspectives can provide a capacity not only to identify and diagnose ecological afflictions, but also help treat or prevent them (Jackson et al., 2017).

Similar approaches have historically been incorporated in agricultural research and extension, but have less effectively accommodated the significance that agricultural and tree management practices have had on the long-term sustainability and values of the ecosystems within which they operate. We are now beginning to pay a price for this lack of awareness in terms of increasing native species extinctions, loss of whole habitats and increasing feral pests and noxious weeds.

Figure 6. Graphic representation of three categories of research – basic, applied and user-inspired – in relation to the roles and end-uses in the research process, and the types of decisions being made. For research results and other knowledge generated or co-developed to support decisions (i.e. management actions, policy decisions or programmatic development), there is often a need for greater involvement with potential end-users throughout the process (Wall et al., 2017). *Note*: This graphic is meant to provide the reader with a visual aid to compare the degree of engagement with end-users across a continuum of research approaches and does not represent an exact determination of the amount of research performed in each of these areas (Wall et al., 2017).



Concluding Remarks

In this paper I have sought to provide an overview of three themes: *Principles for a sustainable society*; *Understanding environmental systems and integrating both ecological and socio-economic processes*; and *Science through a big window – whole-systems science,* which seeks to focus and anchor the main themes of this thesis.

Principles for a Sustainable Society

The following principles will assist us in understanding how sustainable resource use will help maintain ecologically viable life systems (Court, 1990):

1. Sustainable development must grow from within a society. It cannot be superimposed from outside. Cultural integrity needs to be maintained.
2. Sustainable resource use (SRU) must maintain and restore biodiversity and employ sustainable resource use practices.
3. SRU explicitly values equity, provides the basic necessities of life and secures living conditions.
4. SRU will foster self-reliance and responsible local control over resources.
5. SRU will foster peace. (*This is a very difficult condition to satisfy in a presently mainly male-dominated world*.)

While governance for sustainable resource use must allow for mistakes, these should not endanger the integrity of ecosystems and their resource bases.

Understanding Environmental Systems and Integrating Both Ecological and Socio-economic Processes

The above principles need to be linked to research and management actions that address and embody the generic nature of sustainable resource management problems. Translational ecology offers a new paradigm in association with a whole-systems approach, which could effectively contribute to such links.

These frameworks recognise:

- The problems we face are essentially systems problems. Aspects of behaviour are complex and unpredictable. Causes are multiple.

Interdisciplinary, trans-disciplinary and integrated modes of inquiry are needed for understanding.

- They are fundamentally non-linear in causation. They demonstrate multi-stable states and discontinuous behaviour in time and space. *Here useful concepts come from non-linear dynamics and theories of complex systems* (Hollings, 1993).
- They are increasingly caused by slow changes reflecting accumulations of human influences on landscapes and seascapes. They can cause sudden changes in environmental variables affecting sustainability. *Analyses should focus on interactions between slow phenomena and fast ones, and monitoring should focus on long- to medium-term changes in key structural variables of their fluctuating environments* (Hollings, 1993).
- Spatial connections are intensifying so that problems are now fundamentally cross-scale in space and time. *The science needed is not only interdisciplinary but needs to be cross-scale. Multi-level analyses, hierarchical theory, spatial dynamics, event models, network analyses, remote sensing imagery, geographical information systems and parallel processing can assist in opening new ways to handle effectively analyses of more than two orders of magnitude. An understanding and application of the mathematics and modelling of emergent properties as a more powerful link between levels of scale above and below the systems investigated is essential*[3] (Hynes, 1978a; Hollings, 1993; Hynes, 2009; Hynes, 2015).

We have usually been able to achieve satisfactorily linkages between only two or three levels of scale up to the present. We must greatly improve on this performance.

The economical and sociological components, as well as the natural science components, of these problems have an evolutionary character. *The focus for natural science components relates to the dynamics of environmental and ecological change and is evolutionary. The best approach for economics and organizational theory is learning and innovation; and for policies, the best is adaptive designs that yield understanding as well as products* (Naveh, 1979; Hollings, 1993; Hynes, 1994; Hynes, 2009; Hynes, 2010; Hynes, 2011).

The complexities of issues concerning natural resource sustainability are emphasised here. We need to recognise and act on this fact.

Science Through a Big Window – Whole-systems Science

Whole-systems science seeks to draw together the most effective research strategies with regard to key elements of the above principles and understandings. Clearly this requires the judicious identification of multiple objectives and multiple hypotheses relevant to solving the specified system problem. I re-emphasise here that the solutions need to be cross-scale in space and time. Why? Because systems problems are complex, and behaviour is often unpredictable with non-linear causation in these dimensions. The solutions are likely to be beyond any single discipline.

By creatively and selectively employing methods from the toolkit overviewed in this address, we can perhaps for the first time start a more integrated scientific journey into how whole landscape or seascape systems function, one which can assist us to find more effective pathways towards sustainable resource management (Hynes, 2002; Hynes, 2004; Enquist, 2017; Wall, 2017; Jackson, 2017; Hynes, 2020). Time is of the essence here and the urgency immediate.

There is still at least one elephant left in the room. Good science requires good underlying theory, so both theoretical and practical themes need to go hand in hand. It is imperative that we invest serious ongoing effort into developing good theory to underpin whole-systems science.

Three Industrial Revolutions have traditionally been recognised, viz.: First – Coal and Steam, commencing about 1760; Second – Oil and Electricity, 1860s onwards; and Third – Computing, 1960s onwards. We are now experiencing the Fourth – Connected Technologies, 2020 onwards

[3] Ecological and environmental modelling of the systems under investigation can complement these approaches and can be very important in gaining understanding, but that is a subject for another paper.

(Ong, 2020). This is characterised by artificial intelligence, robotics, big data, smart technology, virtual reality, the internet of things and cloud computing, and can logically and effectively contribute to whole-systems science. These technologies when employed in whole-systems investigations are best achieved using highly skilled, cooperative teams, but even then, problems of scale will often demand collaboration with complementary interdisciplinary teams. The days of a solitary scientist working independently are becoming rarer. But invaluable theoretical breakthroughs can still arise from such work, as can ground-breaking traditional reductionist investigations that focus on key processes or specific component problems.

Acknowledging this, all inputs gain from judicious integration when seeking whole-systems solutions. The optimisation of connected technologies can play a fundamental role. Nevertheless, the problems are still system-level problems, and any component integrations need to be conducted in frameworks which, both theoretically and practically, provide the highest level of rigour possible. Crucial component sub-system investigations will need to run in parallel to enable whole-systems solutions. Denialists presently have relatively easy targets because the methodologies do not have theoretical and practical coherence, rational tests of connectedness and verifiable understanding of information-flow between levels of scale in space and time. It seems timely to now consider multi-level ecological analysis (M-LEA) or its contemporary derivatives as a methodology that could contribute to the development of a comprehensive theoretical framework for ecology, as well as providing an applied methodology. This is a paradigm that can strengthen and assist in the optimal use of big data and the IT tools now available to address whole-systems challenges. Further, the M-LEA framework could, I consider, assist in managing scale and information flow between levels. The paradigm could work effectively with TE. There is much work to be done. For the foregoing reasons there is a pressing urgency to invigorate and resource whole-systems science, if we are to contribute effectively and intelligently to solutions of the invidious problems facing humankind in the 21st century (Hynes, 2002; Hynes, 2004; Hynes, 2010; Hynes, 2020).

I watch with interest the currently operating Future Earth program (see Specht & Specht, 2020). This is a UN-associated, decade-long, multi-faceted, exciting international research and knowledge-action initiative, which has implemented a systems-based approach to global environmental and human sustainability challenges (Future Earth, 2020). It recognises our contemporary geologic epoch – the Anthropocene. I have not as yet identified the theoretical framework on which rigorous information flow of the outputs can be optimised by the Future Earth enterprise.

This address[4] has only skimmed the surface. Notwithstanding this, I hope I have sparked some interest regarding where ecological science needs to travel rapidly during this century. This disciplinary challenge needs to be successfully met if we are to contribute to relevant adjustments, crucial to the human use of resources, population stabilisation and pollution management for our species and our increasingly vulnerable biosphere, and survive sustainably with integrity into the 22nd century. However, convincing governments, bureaucracies and the wider community of the urgency and necessity of this need may be the biggest challenge of all.

[4] Hopefully I can explore some of these needs and approaches in relation to scale and information integration in a more detailed paper for our 2021 *Proceedings*.

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