Futures

Mapping regional metabolism: a decision-support tool for natural resource management

Janis Birkeland and John Schooneveldt

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Preface

This report arises from a project entitled "Metabolic mapping as a new decision support tool for natural resource management".

The researchers applied originally for financial assistance for a three-year study to undertake a preliminary sustainability audit of the Australian Capital Region using material flows analysis, and to develop a method of mapping these stocks and flows as an natural resource management decision-making tool.

Land & Water Australia suggested a one-year study to explore the benefits of the approach before considering any wider application of material flow analysis.

In particular, Land & Water Australia asked the researchers to:

1. identify the available data sources in the Australian Capital Region for substances (water, energy and wood) that are necessary for material flow analysis and that are likely to be available in other regions in Australia
2. provide an assessment of available data, identify data gaps, present initial findings for the metabolism of the Australian Capital Region, and highlight the potential merit of mapping regional metabolism.
3. examine in depth the potential usefulness of regional metabolism studies for Australia
4. examine the relationship between the findings of the regional metabolism grant and the grant outcomes for the urban metabolism of Canberra–Queanbeyan
5. provide) some preliminary maps based on available data … to demonstrate/explore their communicative effectiveness.

The report explains and justifies the value of material flow analysis as a method to inform natural resource management at the regional level. It further develops material flow analysis methodology as a heuristic basis upon which to develop strategies to foster rural revitalisation. Also, it resolves some long-standing dilemmas concerning data collection and reconciliation at the regional level by presenting a new approach to the determination of bioregional and systems boundaries.

Finally, the report develops some methodological concepts to facilitate bioregional planning, and demonstrates how metabolic mapping might be further developed and applied more broadly in policy development and community decision making.

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A steering committee was established to provide advice on this project, comprised of: Heather Aslin, Stephen Boyden (chair), Val Brown, Sara Beavis, Tim Cadman, and Helen Sims.

Executive summary

It is widely recognised in Australia that natural resource management (NRM) at the regional level is an essential step towards sustainability generally, and rural and regional revitalisation specifically. However, there is a critical need for improved decision-making processes and techniques for NRM. The report was commissioned primarily to (1) explain materials flow analysis (MFA) and how it works, (2) assess its potential application as a decision-making tool for NRM, and (3) ascertain the availability of adequate data at the regional level for these purposes.

Key issues addressed

- **What is MFA?**

Essentially, MFA calculates the transfers of natural and manufactured material (resources and capital) out of a farm, city or region in relation to those flowing in. However, it goes further than input–output analysis, and examines the transformation of energy and materials within systems. It is a 'metabolic' approach that integrates economic, social and environmental dimensions, and thus provides a basis for 'sustainability auditing'.

- **The potential application of MFA as a decision-making tool for NRM**

The report explains how and why MFA: (a) can be used to resolve existing problems in regional NRM and to guide rural revitalisation; (b) is an improvement over existing sustainability auditing frameworks; (c) can simplify and expedite development assessment methods; and (d) provides a means of finding leverage points for either systems change or eco-innovations at the local level.

Conceptual framework: The report goes further to provide a new conceptual framework to guide the future application of MFA, both as a sustainability auditing and as a development assessment tool. It also provides a new approach to the application of MFA at the regional level, by overcoming a number of long-standing issues in regional planning, including the complexity of environmental quality indicators and integrated assessment models, and problems involved in determining bioregional boundaries.

Leverage points: As a whole systems analysis, this study suggests a number of specific strategies or leverage points to foster rural social, economic and ecological revitalisation in cost-effective ways. These include a discussion of the potential for light manufacturing of bio-based construction materials in regional areas, and the use of 'soil structure' (the water-holding capacity of soils, etc.) as key leverage points from which to address a suite of NRM issues simultaneously (eg. economic diversification, erosion, salinity, biodiversity, loss of agricultural productivity, need for fertilisers and irrigation).

- **The availability of adequate data at the regional level**

The research found that there is no shortage of data from official government sources, but that it is full of inconsistencies. There are discrepancies in data collected by different authorities due to the use of different theoretical frameworks, sampling methods and time scales. This report explains how MFA can be used both to overcome impediments to regional data collection, and to reconcile conflicting data sources. The process of mapping regional stocks and flows has highlighted the need to pursue more work to facilitate knowledge acquisition in a systemic, yet accessible, form that is useful for decision-makers.

- **Innovations**

In essence, this report shows that while development may be the cause of most of Australia's unsustainable practices and resulting environmental problems, development can also be the solution. It reverses the traditional approach of relying on assumed thresholds of nature's resilience to human-caused stresses, and instead seeks to improve (human) systems of management and development. The whole-systems view provided by MFA will enable design improvements to be instituted progressively in cost-effective ways.

There are at least two major innovations that have resulted from this research:

– *Criteria/indicators*

  A means for integrating MFA into on-ground policy and decision-making processes is provided, using a small set of easy-to-apply 'eco-development criteria and indicators' (C&I) to guide development decisions at the regional level. These generic indicators ensure fundamental systems issues are addressed, such as carrying capacity, 'dematerialisation' and 'decarbonisation' of development, and 'genuine progress' considerations. Regional communities can adapt these C&I, and/or add a limited number of region-specific indicators.

– *New concept of boundaries*

  Several practical and analytical barriers to the implementation of NRM at the regional level relating to boundary issues are resolved by the new approach to MFA developed in this report. These barriers include problems entailed in:

  – determining the natural boundaries of bioregions
  – reconciling new regions with existing data sources
  – integrating cultural and political boundaries
  – addressing issues related to complex systems and systems boundaries.

These practical innovations refocus regional material accounting toward the health of key natural systems and the health effects of stocks and flows of critical materials and substances. They also put NRM on a proactive footing, directing investments toward continuous improvements, rather than remedial action focusing on symptoms.

The report concludes with a section that relates MFA techniques to LWA's four over-arching themes.

1 Introduction

1.1 Development as the problem

As the global population reaches the 10–11 billion mark over the next 40 years, it is necessary to reduce per capita material and energy consumption by over 90% in order to achieve sustainability. This imperative is known as 'Factor 10' in Europe (von Weisacker *et al.* 1997; WBCSD 1997; Hawken *et al.* 1999). There is no option if we are to meet human needs equitably within the Earth's carrying capacity.

It will be physically impossible for developing nations to achieve Western material living standards with existing technologies, as the 'ecological footprint' [the equivalent land and water area required to produce a given population's material standard, including resources appropriated from other places] already greatly exceeds the carrying capacity of the planet (Wackernagel and Rees 1996).

In recent years, major innovations have increased eco-efficiencies in manufacturing and agriculture. For example, carbon fibres and other new materials support about 10 times the weight as the same quantity of metal did in 1800 (Gardner and Sampat 1998, p. 28). However, net resource, toxin, and energy flows have increased at a faster rate, due to increasing supply-driven production and consumption. In the next 50 years, global economic activity is expected to increase roughly five-fold, while manufacturing activity, energy consumption, and the throughput of materials are likely to rise three-fold (Lash *et al.* 2000).

> Materials intensity — the tonnage of material used to generate a dollar's worth of output — declined by 18 percent between 1970 and 1995 … however, total consumption of material swelled by 67 percent between 1970 and 1995 (Gardner and Sampat 1998, pp. 26–27).

Economic growth must therefore be 'decoupled' from resource use and waste generation through the 'dematerialisation' of the economy [a reduction in the resource and energy intensity of products and processes]. We believe such a dramatic level of 'dematerialisation' is theoretically possible to achieve — but only if systems of production, construction and distribution are fundamentally *redesigned*. Eco-innovation is required in all areas of development, including resource extraction and production processes, the design of the built environment and infrastructure, and land-use planning.

While radical resource productivity will not achieve all the other changes to social relations, political institutions, built-environment design, and urban form that are necessary for sustainability, it is an *essential* component. The achievement of sustainable regions will require that Australian business and industry move rapidly beyond 'eco-efficiency' toward prevention — and beyond to 'eco-effectiveness'.

Material flows in development: Historically, NRM has focused on problems at the source of extraction (forests, mines) and production processes (farms, factories), but not on the *design* of development itself (infrastructure, settlements, buildings, products). That is, environmental management has focused on the far ends (input and output) of the production line, not on systems design. Hence, NRM has concentrated on mitigating impacts, rather than redesigning the human systems that create the demand upon the environment in the first place. The following are some examples of the reasons for the need to appreciate the centrality of material stocks and flows in development itself, in addressing environmental problems:

Carbon flows: Next to energy sources, buildings and infrastructure are the largest source of carbon flows. Some 25% of CO_2 emissions are attributable to the operation of buildings, and 50% of CFC emissions. Due to its organic content, the landfill of construction materials (roughly 44% of landfill content and 50% of packaging waste) contributes greatly to methane and greenhouse emissions as well.

Nitrogen: Apart from producer and consumer goods, most nitrogen inputs into urban areas are from construction materials, and most nitrogen stocks are hibernating in construction materials — due to the increasing use of synthetic materials in construction. The substitution of organic building materials could alleviate much of this problem. At the regional level, of course, nitrogen is caused largely by conventional agriculture. This could be improved by changes in agricultural practices and/or changes in dietary habits away from meat-based diets which produce large nitrogen inputs and outputs (Obernosterer *et al.* 1998, p. 47).

Metals: About 90% of stocks of metals are located in city infrastructure and buildings (eg. lead in water pipes, aluminium in windows, iron in steel, gravel and concrete). The amount of emissions from these metals into the environment is not known, but there is seepage into soils and underground water from corrosion and wear. Leakage of lead in older buildings is a well-known hazard: a potent neurotoxin, lead harms brain development (children absorb up to 50% of the lead taken into their bodies, adults absorb 10–15%).

1.2 Development as the solution

The built environment is a major component of the 'demand' upon the environment (excluding military investment), and it is, in most cases, the easiest area in which to reduce resource consumption. For example, ecological retrofitting can improve the operating energy efficiency in housing by up to 90%, yet pay for itself in a few years — often immediately — due to increased capital value (Nevin and Watson 1998; EPA 1998). On a national level, eco-logical improvements to the existing housing stock with simple design technology (insulation, solar heating, better windows) could reduce a country's annual energy bill by 50%.

Environmental design in commercial buildings has meant improved profits for business. For example, the well-known ING (previously NMB) bank in Amsterdam uses 90% less energy per square metre than its predecessor. It cost $0.7 million extra to build, but has saved $2.4 million a year, plus another $1 million annually through reduced employee absenteeism, due to a more pleasant work environment. Hence, the one-off investment of $0.7 million has resulted in around $3.4 million dollars extra income a year through design.

Likewise, the green design or retrofitting of office buildings pays dividends through increased worker health and productivity, as well as through significantly reduced operational costs of buildings. For example, by improving the lighting in a post office, which cost $300,000, worker productivity increased by $500,000 a year and another $50,000 is now saved annually in energy costs. That is, a one-off investment of $300,000 has meant over $0.5m a year extra income (Romm 1999).

The past failure to examine material flows in the built environment: Early environmental management methods were derived from the 'hard' sciences, and hence were designed to describe, measure and monitor the pollution levels in the air, water, soil and biota. An underlying source of pollution was due to the reliance upon fossil-fuel based materials and construction processes. This form of development went unchallenged because it was generally accepted as synonymous with 'progress'. An integrated, whole-systems approach to regional planning and environmental management has not yet been developed that can enable decision-makers and citizens to fully comprehend the interdependency of natural and human-made systems, and the pathologies created by industrialised development. A couple of reasons for this, related to the institutional culture, are as follows:

- *Theory:* Traditionally, many environmental systems issues were segmented and studied as separate disciplines. For example, urban and rural issues have been treated as different systems. This reductionist approach had a tendency to mask externalities, such as agricultural run-off from rural areas affecting the water quality of downstream populations.
- *Practice:* Environmental managers have divided professionally and academically into those concerned with problems at the source of extraction (wilderness and biodiversity protection) or pollution at the site of production (industry or agriculture). As mentioned above, this linear approach (extraction–use–waste) led to solutions that mitigate impacts, but fail to address new systems design opportunities.
- *Policy:* Most environmental-policy-related disciplines borrowed decision-making concepts and methods from economics (eg. benefit–cost analysis), while even the environmental sciences have been slow to take on the full meaning of complex systems — perhaps because environmental policy has been dominated by economic concerns. This approach has led to trade-offs rather than system-wide improvements.
- *Legislation:* Environmental regulation has been influenced by legal frameworks that were concerned with, among other things, 'interest balancing', or the respective rights of developers, stakeholders and the general public to environmental benefits. Only comparatively recently has environmental responsibility been factored into the rights-based legal ethic.

None of these frameworks for environmental problem solving encouraged a whole-systems approach: that is, improving the health and resilience of the fundamental underlying life-support systems. Instead these frameworks favoured trade-offs that relied upon establishing the limits of nature's capacity (thresholds) to sustain itself under many kinds of interacting pressures.

To escape the vestiges of these linear and reductionist intellectual frameworks, environmental problem solving needs to become less concerned with accumulating descriptive knowledge and refining methods to make trade-offs, and more outcome-oriented and focused on social construction and systems design.

For reasons mentioned above, environmental legislation, management and conservation measures can only slow the degradation and diminution of Australia's land and water resources. Ecological sustainability and biodiversity require that agricultural and manufacturing industries must, over time, be transformed to function within the limits of the carrying capacity and ecology of a bioregion (without sacrificing life quality). To achieve this, tools for integrated approaches to NRM must be developed, by which we can:

- comprehend whole systems and their demands upon land and water resources: urban form and infrastructure, construction and agriculture, services and distribution systems — as well as their interdependencies
- guide the redesign of the human-made systems (or 'anthroposphere') at all scales from products to regional infrastructure.

1.3 Proposed tools for bioregional NRM

Natural resource management at the bioregional level (bioregional NRM) is a key step towards sustainable development and, in particular, rural and regional revitalisation. This report suggests how regional sustainability audits, using MFA, can have positive ramifications on regional empowerment and decision-making: potentially reversing rural economic decline, diversifying regional industry, assisting desalinisation and biodiversity conservation, lowering fuel costs, and value adding in regional production (as explained below). A new method is outlined in this report for conducting regional metabolism studies to address crucial issues facing NRM and regional Australia.

MFA: Essentially, MFA calculates the transfers of natural and manufactured material (resources and capital) out of a region in relation to those flowing in. However, it goes beyond recording information on resource transfers in terms of input–output analysis, and focuses on the transformation of energy and materials *within* a region. Such a 'metabolic' approach provides a sustainability audit that can integrate economic, social and environmental dimensions.

The successful application of this technique will require the meaningful involvement and sense of ownership by local stakeholders. Visualisation tools are therefore needed to facilitate public understanding of complex regional development issues in relation to fundamental systems. Metabolic maps are dynamic, visual diagrams of material flows (unlike traditional geographic maps that identify static features). They are an appropriate scientific and pedagogical tool to use in situations where other forms of modelling are not practical (Zilman 1996, p. 77).

Innovations: There are two specific innovations to improve MFA at the regional level that have resulted from this research.

One is a means for integrating this form of analysis into policy and decision-making processes, using a set of easy-to-apply 'eco-development C&I' (criteria and indicators) to guide development (eg. agriculture, housing, manufacturing) at the bioregional level. The key elements of the C&I for assessing development are:

- development should be designed to maintain the same level of *ecosystem services* as before the development took place
- for renewable materials (eg. 'bio-based materials' which are made from agricultural waste), this can best be achieved through the maintenance of soil structure (discussed in Section 4)
- for non-renewables, the 'extraction–use–waste' process should be replaced with systems that maintain stock levels and constantly reuse that stock.

These basic eco-development C&I need to be seen in the context of the regional framework described in Section 3. If the design criteria/indicators set out in Table 3 are progressively applied, sustainable NRM is a possibility. This approach focuses on how to improve systems health. It is a systems design approach and thus differs from the traditional science approach of trying to model complex systems. Modelling offers a powerful research tool but is impractical and even risky in relation to general decision-making and planning.

MFA provides a useful conceptual framework to guide the selection of, and planning for, ecologically appropriate land uses, to identify new sources of rural income, and to enable local communities to identify performance measures (indicators) to monitor the application of the above design criteria/indicators appropriate to their region. These criteria/indicators supplement those we have proposed for urban development in another study (Birkeland and Schooneveldt 2002).

Boundaries: There are several theoretical and practical issues that have plagued bioregional NRM for decades. Key issues needing resolution are: (1) defining bioregional boundaries; (2) reconciling them with existing data sources and decision-making boundaries; (3) establishing analytical systems boundaries; and (4) conforming disparate natural, political, cultural identities into geographic areas. Section 3 of this report provides a resolution to these issues.

The proposed approach uses material flows analysis (MFA) to map fundamental limiting natural systems (eg. water, energy, arable soil, salinisation), not according to regional boundaries in the first instance, but according to their individual dynamics and systems boundaries. This differs from the traditional preoccupation in the literature of bioregionalism of attempting to conform decision-making jurisdictions with ecological boundaries or vice versa. This provides pragmatic solutions to these boundary problems by isolating, mapping, and overlaying critical materials and substance flows according to their systems boundaries — as constrained by countervailing human-caused forces and natural conditions.

2 Bioregional natural resource management and materials flow analysis defined

2.1 Bioregional natural resource management (bioregional NRM) defined

Because this research integrates bioregional NRM and MFA, Section 2 defines both fields and outlines their advantages over, and contributions to, traditional approaches. It then lists some of the gaps and shortcomings of bioregional NRM and MFA as presently theorised and practised. Finally, it identifies ways in which the integration of bioregional NRM and MFA can address shortcomings of both fields. The dilemmas resolved by the cross-fertilisation of Bioregional NRM and MFA (listed in the introduction) are explained in detail in Section 3.

Mainstream bioregional NRM: Bioregional NRM is an emerging field based on the view that land-use planning and natural resource management should be undertaken at a bioregional scale. It is only recently that the term 'bioregion' has become part of the standard vocabulary of planners and environmental managers in Australia. A major conference on bioregional NRM was convened by Department of the Environment, Sport and Territories in 1995 and the *1996 State of Environment Report* documented progress in Australia in this area. In Australia, as well as Canada and the US, advances in the field of bioregional NRM have largely been in the area of resource and land-use inventories (including the continental shelf), or geographic mapping related to specific issues like biodiversity conservation.

Bioregionalism distinguished: Bioregional NRM has drawn upon 'bioregionalism', a movement which developed within the broad spectrum of the green movement from the 1970s. Bioregionalism begins with the proposition that human cultures co-evolved with nature and are and always will be interdependent. Bioregionalists hold that by 'living in place' and coming to understand their local ecology, people would make better decisions about land use and development. There has been a growing convergence of bioregional principles and mainstream planning, as more people exposed to bioregionalism and other forms of eco-philosophy have entered the resource-management professions.

Bioregional principles address the need for an integrated conceptual framework on a regional scale and provide a vision and a process for envisioning the future. However, bioregionalism lacks adequate methods to put those principles in practice. Advances in bioregional NRM methods and processes are developing rapidly, but are still plagued by many theoretical and practical problems. MFA could fill these gaps. Some of the principles contributed by bioregionalism to NRM are described below, with some observations on how MFA would assist their implementation.

Principles of bioregionalism

Ecologically appropriate land use

Bioregionalists hold that human settlements, agriculture, manufacturing, urban infrastructures, construction and other systems of development, should be transformed to function within the limits of the carrying capacity and ecology of a bioregion. To achieve this, systems must be redesigned along the lines of ecological or 'closed loop' systems, where waste is avoided or treated as a resource; that is, a circular rather than a linear metabolism. (A linear system that converts waste to a resource is exemplified by worms and the whole class of organisms known as decomposers; they are 'linear systems', but they perform in the opposite way to factories.)

As a derivative, settler nation, Australians adapted large-scale agriculture and centralised urban planning and design processes. They did not modify their behaviour to suit the more fragile Australian landscape. The resulting environmental degradation is threatening to reduce the productive capacity of much of this continent. It is costing the Australian economy billions of dollars in lost revenue. The cost of managing waste in Australia is $2.5 billion a year. By implementing ecological design principles, however, most of this waste could be converted into resources.

Bioregionalism advocates not only industries that avoid waste, but crop selection, food consumption and lifestyles that are compatible with the region's natural ecosystems. The waste of arable land may be more damaging in the long run than emissions and other by-products of production. There has been a shift from food for human consumption to production of (non-native, hoofed) animal food products which, although value adding, are not the most eco-efficient use of limited nutrients. By 2050, Australia could be facing the loss of 10 million hectares of productive arable land from the wheat–sheep zones in eastern and western Australia. US feedlot beef converts about seven pounds of grain into just one pound of meat (Hawken *et al.* 1999, p. 206). Cows emit about 72% of all livestock methane, and a typical cow produces 280 litres of methane a day (Jones 2000, p 3).

MFA shows graphically that the higher up the 'food chain' the food source, the more materials and energy are consumed in its production. Shifting some meat consumption towards less ecologically costly animals (eg. kangaroos and fish), for example, could reduce these flows. MFA can thus be used to determine suitable industries for a bioregion.

Shift to bio-based systems

Another implicit principle of bioregionalism is a shift to a bio-based production system. Almost everything that can be made from hydrocarbons (fossil fuels) can be made from carbohydrates. Some 25,000 products made from hydrocarbons can be made from plants (eg. bamboo, straw, non-narcotic forms of hemp). Products made from plant matter can be recycled and avoid most toxins dispersed by hydrocarbons throughout material and product life cycles. This includes the use of plants as a resource for healthy materials and biochemicals (in place of petrochemicals). Bio-based building products and packaging could be composted to eliminate some of the construction waste that accounts for 44% of landfill.

North America is moving rapidly ahead in the development of (agriculturally derived) 'woodless timbers' and other bio-based construction materials. For example, while Australia sold its only strawboard manufacturing plant equipment to the US, strawboard manufacturing is growing at a faster rate than conventional particleboard in the US. At least three North American manufacturers produce particleboard of straw instead of wood, and another is producing a particleboard made from bagasse.

MFA shows that the life-cycle costs and externalities of bio-based materials are far less than conventional construction materials.

Regional diversity

Each region offers different environments and hence different resources, constraints and opportunities for ecologically suitable crops, industries, products and services. If a rigorous version of bioregionalism were to prevail, the culture, economy, architecture and products of different regions would gradually become differentiated, creating distinctive regional qualities tailored to the natural environment. CSIRO reflects a bioregional (as well as a permaculture) ethos when it suggests that halting dryland salinity — and the related loss of biodiversity — will require different land uses for different climates, soils and hydrological conditions of each catchment.

> To realise this vision, we will need to pioneer the development of a new landscape, a mosaic of tree crops driven by large-scale industrial markets such as biomass fuels and high-value annual crops, as well as mixed perennial–annual cropping systems, and areas devoted to maintaining those elements of native biota dependent on native vegetation. (CSIRO 2000, p. 2)

The CSIRO report acknowledges that the tools required to determine the best mix of plants and other land uses are not yet adequate for the task (p. 23). The 'green revolution' [the global push for industrial agriculture of the 1950s and 60s] led to a growth in world fertiliser use from 14 million tonnes in 1950 to 129 million tonnes in 1996 — with extensive environmental impacts (Gardner and Sampat 1998, p. 13). However, this has led to increased nitrogen fixation which has reduced species diversity and even has the potential to cause brain damage or death in infants (Gardner 1997, pp. 10–13).

Organic compost can replace fertilisers to a large extent. It traps more nutrients, retains more water and air than other soils, and ensures a more balanced soil ecosystem that suppresses plant diseases; it therefore also avoids the use of deadly fungicides such as methyl bromide (Gardner 1997, p. 25). Considerable work is being done to develop compost that can be aligned with diverse soils, crops, and ecosystems. Composting toilets cost one-seventh that of conventional sewerage systems, and avoid the need for capital-intensive infrastructure and pipes in low density areas. "The entire province of Tunum in Sweden is converting to composting toilets and … Nitrogen and Phosphorus pollution has been reduced by 90–95%." (Roodman 1998, p. 48).

MFA can assist in determining which stocks and flows of substances (eg. nitrogen, phosphorus) are too high, and in determining the optimal mix of land uses in a region.

Social action

A key element of bioregionalism is social action and participatory democracy. It is held that local citizens often have the best knowledge of local environmental and social issues, but generally lack ecological literacy (with the exception of a significant portion of farmers).

> Studies show that the average child in the US can recognise 1300 corporate logos, but only 10 plants and animals native to the bioregion. (McGinnis 1999, p. 7)

Even farmers lack the time and resources to think about the future and cumulative consequences of the present choices they are making. The process of bioregional planning is seen as a potential vehicle for environmental education: learning to 'connect with' and 'reinhabit' the bioregion. However, it relies on ecological awareness of citizens and decision-makers, and has not developed adequate analytical tools to enable the translation of these ideals into reality.

Understanding human interconnectedness with nature is not enough to motivate change. People need to understand how environmental issues affect things they care about, such as their personal health and pocketbooks, or development of their children. Unsafe environments (unclean air, water and sanitation, floods, droughts) cause literally millions of children to die — needlessly — each year. The World Health Organization has estimated that at least 25% of global disease and injury is linked to environmental degradation and "as much as two-thirds of all preventable ill health due to environmental conditions occurs among children" <www.who.int>. In turn, most diseases, deaths and injuries resulting from environmental degradation can be linked to conventional forms of industrial development (which are highly subsidised).

Subsidies have prevented the internalisation of the true costs of industrialised agriculture, and therefore obstruct ecological literacy and true public choice. For example, subsidies for agriculture provided by the 29 member nations of the OECD total $300 billion per year. They have often been bad for the environment, and ultimately bad for farmers. According to Roodman (1998, p. 37): "For the amount of money spent, pesticide subsidies are probably among the most damaging to the environment (and to farm worker's health)". Government "subsidizes agricultural production, agricultural nonproduction, agricultural destruction, and agricultural restoration, and for good measure, it subsidizes crops that cause death and disease, by giving over $800 million a year to tobacco farmers" (Hawken *et al.* 1999, p. 162).

MFA can help identify the true costs of subsidies and other cases of economic inefficiency, and assist decision-makers in determining the best policy options for eliminating hidden subsidies that militate against economic rationality. By tracing flows through a region, citizens can become informed as to the true ecological/economic 'trade balance' of their region, which eventually translate into political pressure and economic responses like import substitution.

Methods of bioregionalism

While some of the visions and principles of bioregionalism have been adopted by NRM, deliberately or by osmosis, its planning techniques have contributed little overall, due to some unresolved issues. There are two key steps in bioregional planning: boundary definition and resource inventories. These processes can be enhanced by MFA.

Boundary setting

Bioregionalism begins with the determination of bioregional boundaries, guided primarily by edges between natural regions having different vegetation, climates or topography. It is understood that natural boundaries are permeable, fluid, and change over time, as climate and other natural processes are modified. Nonetheless, it is considered essential to define natural boundaries so that political and economic policies can be tailored to regional conditions and ecosystems. A longer term objective is the convergence of natural and social regions into one system of ecogovernance. The importance of aligning social decision-making jurisdictions with natural systems has spawned a debate in the bioregional literature over how to determine boundaries.

Boundary criteria: Various criteria are used to define bioregional boundaries. Dodge (1981) suggested six:

1. biotic shift – the percentage change in species of flora and fauna from one region to another
2. watersheds – catchments or groupings of the catchment areas
3. land forms – geological features and soil types
4. elevation – different elevations support different flora and fauna
5. cultural patterns – indigenous people have retained knowledge and practices that evolved with their bioregion
6. spiritual places – local factors influence the development of place-centred spirituality.

Nested hierarchies: The dominant view in bioregionalism is that there are several levels of bioregional organisation, each of which fits inside the next larger one (Sale 1985). In order of descending size, the levels are:

1. an 'ecoregion', such as an island or desert region;
2. a 'biome' – an ecological community (such as grasslands or wetlands), a 'georegion' or a geological region (such as a range of mountains or discrete section of coast); and
3. a bioregion (such as a catchment). The larger regions are made up of component bioregions, but a bioregion may cross or straddle a biome/georegional boundary.

It should be noted that these geographic concepts are based on a mix of species, ecosystems or human values, making the concept as well as the criteria of boundaries somewhat rubbery. Bioregional NRM has simply defined boundaries without addressing all of the inherent issues and ambiguities. We address the problem of boundary setting in a later section.

Resource inventories

The second step in bioregionalism is to make an inventory of both biotic and abiotic resources, which draws on local knowledge of residents and the natural history of the region (including traditional Aboriginal knowledge). Information on flora and fauna, climate, landforms, human ecology, resource potential, existing settlement patterns, demographics and so on, are combined to create a 'directory' of the bioregion. The analysis of the resource inventory and carrying capacity of the bioregion provides the basis for redesigning systems of production and construction to increase regional self-reliance and eco-efficiency. However, the bioregional literature does not appear to explain how to do this. Inventories are static and do not give adequate information on the inefficiencies of development processes in the region, resource transfers from rural to urban areas, cross-subsidies, or the build-up of chemicals in groundwater, and so on. Bioregionalism needs methods of analysis, such as MFA, that can measure resource flows in and out of a region to identify imbalances. MFA can thus anticipate environmental problems and trace symptoms to their sources.

2.2 Material flows analysis (MFA) defined

A significant international trend is to analyse environmental problems that result from the design of human settlements and land-use systems by analogy to metabolic systems. Just as biological organisms have particular inputs, outputs, regulating and transformative processes and links to the wider environment, so do industrial plants, urban areas, economic zones, and regions. Even whole nations can be seen to take in nutrients/resources/energy, transform these into useful materials or products, and dispose of waste. In natural metabolism, of course, there is no waste. Reefs and rainforests self-regulate, by replacing goods extracted for human use. However, both resource extraction and waste has exceeded the carrying capacity and regenerative capacity of many of these bioregions.

Most environmental problems can be understood in terms of these inputs, outputs and transformations. As outlined by Boyden (2001):

- *Inputs:* At the urban scale, disruptions to ecosystems result from impacts related to metabolic inputs, such as the harvesting of vegetation for food, timber and fibres (causing soil erosion, salinisation, disruption of nutrient cycles, loss of biodiversity and the progressive colonisation of the natural world).
- *Outputs:* Chemical pollution is associated mainly with metabolic outputs (causing acid rain, heavy metals, contamination of rivers with nitrogen and phosphorus, greenhouse emissions and ozone depletion, and the release of an increasing number of toxic substances into the biosphere).
- *Transformation (internal metabolism):* Energy and resource consumption are particularly associated with internal metabolism in transportation systems, infrastructure and facilities, consumerism, heating and air-conditioning buildings, and products.

Internal metabolism: Until recently, environmental analyses have focused on the inputs and outputs of urban areas, rather than the *internal* metabolism or the transformation of materials into products and waste. For example, environmental managers focus on the extraction and milling of timber at one end and construction waste at the other, but not on waste in design and construction throughout a log's life cycle. The transformation of timber materials into structures has been left to developers and architects that are not trained to think in terms of material stocks and flows. As a result, wood is being used inefficiently; only about 5–15% of the tree ends up in finished wood products.

In practice, life-cycle analysis (LCA) is often undertaken within narrow systems boundaries. LCA can trace energy inputs through each step in timber extraction, processing, manufacturing, transport and construction process to its final resting place as the wall stud in a home. However, it does not look at potentials for closing waste loops through new products or processes.

Regional metabolism: Tracing the flow of materials and calculating transfers of natural and manufactured material (resource and capital) out of a region ('regional metabolism') in relation to those flowing in, provides a 'sustainability audit' of a region that integrates economic, social and environmental dimensions. However, MFA provides a planning tool that quantifies and measures the stocks and flows of materials through urban, industrial, and regional areas and traces them to their sources. It also links the flows to the natural systems in which they are embedded.

2.3 MFA and rural Australia

MFA provides a whole-systems view that can begin to find solutions to the long-term problems facing the rural economy that were caused by conventional 'industrialised' agriculture perspectives.

Three examples help to illustrate how a MFA can shed a different light on agricultural issues:

Example 1: MFA shows the degree of dependency of the urban centre with its hinterland for the supply of goods (eg. water, energy, construction materials) and for disposal (via air and water). Further, MFA shows where regions are 'out of balance' in terms of material and energy imports and exports. MFA can also identify areas of waste, and options for new agricultural products and services that are more sustainable and marketable. This information will enable regions to identify export substitution industries and products to reduce dependencies on external regions.

Example 2: According to the (US) National Research Council, between one-third to one-half of nitrogen fertilisers are not utilised by the plants and up to 90% of pesticides miss their target insects and disperse into the environment. Most of this eventually ends up in rivers and aquifers. The impacts are often not visible or measurable until it is too late, because it takes many years for pollutants to leach through the ground into aquifers. Groundwater stores pollutants longer than flowing rivers because, among other things, they have less microbial action to break down chemicals. These aquifers are also being drained for irrigation, which accounts for two-thirds of water extraction from rivers and aquifers worldwide. Nitrate pollution in groundwater reduces crop

Box 1. Metabolism explained by example (soils)

An agricultural example is used to distinguish linear and circular metabolism.

Agrarian societies were characterised by circular metabolisms, because nutrients from crops, animals and food wastes were deposited back in the region. Urbanisation introduced linear systems, where goods, substances and wealth moved primarily from the hinterland to the city (Gardner 1997). The export of food from fertile regions to urban areas meant a transfer of organic matter to the places where the resources were consumed. This gradually depleted surrounding regions, often leading to the collapse of civilisations (Girardet 1996). However, the invention of chemical fertiliser in the late 1800s enabled urban expansion by reviving (temporarily in the case of Australia) the fertility of tributary farmland areas.

Consequently, garbage and sewage in urban regions became 'waste' rather than soil builders. Cities produced more solid and liquid waste than the surrounding terrestrial and aquatic ecosystems could assimilate. In the long term, this linear flow of nutrients led — at one end of the pipe — to costly sewage disposal, drinking water contaminated with fertiliser run-off, reduced species diversity due to excess nitrogen, and the suffocation of rivers and lakes with algal blooms. At the other end, it led to landfills leaching chemicals into groundwater and rivers, methane into the atmosphere and so on (Gardner 1997, pp. 5–7).

Australia's soil problems

Australia's relatively infertile soils need more organic content, and better soil structure. A circular metabolism could be created by returning natural organic nutrients to the soil and treating waste with worms and microbes. Some examples follow.

- Compost builds soil by trapping more nutrients, retaining more water and air than other soil, and suppressing plant diseases — thus avoiding the use of chemical fungicides.
- Micro-organisms and other decomposers can reduce the level of toxins and oil in soil ('bioremediation').
- 'Living machines' use ecosystems to break down sewage and other pollutants through a series of open tanks (Todd 1999, 2000) and use sunlight to kill harmful bacteria.
- Artificial wetlands, or waste stabilisation ponds, are about one-quarter the cost of conventional sewage-treatment plants, and can also produce healthy fish.
- The SIRDO system (household toilet) uses a solar-heated, double-vaulted system to produce an odourless biofertiliser.
- Biogas digesters are being developed for use in large buildings to produce methane and biofertiliser.

Currently, wood residue and wood chips are burnt (euphemistically referred to as 'pyrolysis') to generate electricity (which causes greenhouse gas emissions) on grounds that there is not another use for this organic 'waste'.

production and weakens crop immunity to disease. Given the economic infeasibility of cleaning underground water, prevention is the only cure. The invisibility of groundwater pollution is a major cause of its being overlooked. MFA can be used to make this 'visible', by adding the amount of contaminants from cattle yards, mining, pesticides, fertilisers, and so on, that are entering the groundwater and which eventually accumulate in rivers and oceans. (Current LCA studies measure pesticides but do not add up flows that get into the water systems: the analysis stops where pesticides reach the water.)

Example 3: The literature suggests that conventional approaches to value-adding in the rural sector are flawed from an ecological perspective. Plant matter is treated primarily as a raw material for food production. However, high value-added food products benefit individual companies more than the regional economy as a whole (Morris and Ahmed 1993). Increased food processing will do little to assist farmers who are receiving an ever smaller percentage of profits from food production, while an increasing share goes to food processors and distributors. Moreover, food export markets are becoming increasingly competitive.

> The huge export subsidies that industrialised nations use to expand foreign sales not only burden their public budgets but undermine agricultural sectors in Third World countries, accelerating the exodus from rural areas to overcrowded, inadequately provisioned cities. (Morris and Ahmed 1993, p. 1)

A better form of value adding is through:

- *New rural enterprises:* Plant matter can be more than a raw material for food production. Petrochemical substitution products can be produced through light manufacturing in rural areas — such as farmers cooperatives to establish biorefineries for ethanol, compost plants to replace chemical fertilisers, or fabricate building materials (eg. strawboard).
- *Healthy products:* Plants can be used as a resource for healthy materials and bio-chemicals (to avoid petrochemicals), to reduce the adverse (ecosystem and human) health impacts of construction materials. In France and the US, for example, homes are already on the market that almost exclusively use bio-based materials (such as insulated, structural, compressed straw panels for the walls, floors and roof, as well as interior shelving, cabinets and built-in furniture).

  MFA could identify areas of waste, options for new agricultural products and services that are more sustainable and marketable, and export substitution industries and products to reduce dependencies on external regions.

2.4 How MFA can contribute to NRM methods

MFA can complement, or in some cases replace, other forms of sustainability frameworks, such as ecological footprint analysis or industrial ecology. It can also supplement, or in some cases replace, other forms of building and product analyses, such as environmental impact assessments (EIA), life-cycle analysis (LCA) and embodied energy (EE). The following paragraphs outline some of the shortcomings of these sustainability frameworks and development-assessment tools that MFA can support or improve upon.

Ecological footprint analysis has focused on equity between urban areas and their hinterlands. This clearly and visually shows the problems, but does not tell us how to fix them. Equity has not been a driver of environmental decisions. MFA is less abstract. It can show the urban areas that are 'out of balance' with their region in terms of material and energy imports and exports. By tracing flows through a region, citizens can become informed as to the true ecological/economic 'trade balance' of their region. Evidence of where local citizens are losing out is more likely to result in political pressure (and subsequently economic responses like import substitution), than is evidence that they are getting more than their fair share of global resources.

Industrial metabolism has focused on developing networks of industries to create eco-efficiencies, but has largely failed to address the need to reduce demand on industry for *more* products and throughput. This 'rebound effect' will also continue to reduce net efficiency gains. Reducing the total flows requires not just pollution prevention in factories, but also the redesign of the anthroposphere. Substantive life quality improvements which meet basic social and emotional needs are also essential in reducing consumerism (which is arguably a substitute for meaningful living). Genuine progress indicators (GPI) are beginning to account for this personal dimension, but these indicators do not yet address the role of the built environment and design in meeting subjective needs.

Urban metabolism has focused on the inputs and outputs of urban areas, rather than the *internal* metabolism or the transformation of materials into products and waste, where systems design changes can often be the most cost effective. Total material use has *increased* by two-thirds since 1970 (Gardner and Sampat 1998, p. 27). Construction materials expected to be used in the US between 2000 and 2030 are projected to exceed the total use in the 20th Century (Gardner and Sampat 1998, p. 43). Basic extraction and processing activities, such as mining and logging, account for 75% of the energy used by industry. Much of this resource extraction feeds the construction industry, as buildings consume roughly 40% of world materials flow. The redesign of the urban environment has the most potential for a radical resource reduction.

State of environment (SoE) reports: SoE reports describe environmental conditions and sometimes go further to trace larger cumulative impacts to their logical conclusion under business-as-usual scenarios. SoE reports in Australia are invaluable but, to date, are a collection of information with a discussion of general implications. They do not analyse alternative options and calculate payback periods or cost savings that are possible under 'best practice' eco-efficiency strategies. In contrast, scenario and least-cost planning are facilitated by MFA, making proactive planning and management possible (see Box 3).

Embodied energy/life cycle analysis: Embodied energy and life cycle analysis are not appropriate analytical tools for looking at the total impact of materials and buildings in an urban area. They are 'bottom up' approaches that are highly complex and difficult to aggregate. MFA gives totals of energy and materials, and the cumulative impacts that we can attribute to buildings (on average) through a 'top down' approach which could save vast

Box 2. Summary of advantages of MFA

By determining areas of waste or inefficiency, and tracing these to their social, structural and industrial sources, metabolic mapping has the potential to assist primary producers, decision-makers and the community at large, in:

- understanding the complex interdependencies of human systems and their bioregions
- providing a basis for looking at urban, industrial, and agricultural systems together as one system
- establishing a resource balance between rural and urban areas and between different regions
- measuring resource/wealth transfers associated with alternative regional development scenarios
- preparing regional sustainability audits and plans to guide future development
- evaluating the potential impacts of policy initiatives
- identifying areas where public interventions bring investment returns (eg. pollution prevention or bioremediation programs)
- finding leverage points where business and industry can profit through eco-efficiencies or new green enterprises
- providing early warning of pre-crisis environmental conditions (build-up of toxins) enabling correction before they become irreversible
- assisting public and private sectors in visualising the long-term implications of planning decisions
- determining the most suitable urban, industrial or agricultural systems appropriate for particular bioregions
- finding gaps or inconsistencies in data or information and reconciling them
- comparing existing conditions to pre-settlement conditions to guide restoration ecology
- dealing with large-scale conditions and cumulative impacts
- analysing least-cost approaches to development
- determining priorities for strategic planning, policies and programs,
- revealing which activities are transferring wealth out of the region
- making externalities visible (eg. urban and agricultural run-off)
- providing a basis for criteria and indicators and improved ecological design guidelines
- linking actions to the improvement of fundamental systems conditions (eg. decarbonisation and dematerialisation)
- informing policies that would increase regional self-reliance
- identifying stocks of materials and substances building up in the anthroposphere for 'resource mining'
- indentifying where the greatest non-point impacts are occurring
- identifying opportunities for the commercialisation of more sustainable products and services
- identifying potential new regulatory approaches at local, regional and state levels (eg. educational, legislative, eco-design strategies)
- incorporating subsidiary concepts like 'ecological footprints' and 'ecosystem services', to assist in a shift to a whole systems understanding.

amounts of processing. Our proposed simplified set of indicators make bottom up data compilation much easier as well.

Environmental impact assessment (EIA): EIAs tend to limit choices to land-use options that happen to be available when a proposal is put forward by development interests. Consequently, the decision often turns on the 'highest economic use', rather than the optimal use of land, resources and human capital. Also, EIAs are not designed to deal with regional and cumulative impacts. They orient decision-making towards case-by-case approaches, which are inherently biased against sustainability. Further, EIAs are often disempowering due to technical (if not obfuscatory) language, whereas metabolic maps (with GIS visualisation tools) will enable more meaningful citizen input.

Environmental quality indicator (EQI): EQIs have largely been centred on *impacts* of human activities on the environment, such as the levels of toxins and pollutants in air, soil and water. Indicators based on the stocks and flows in the anthroposphere (infrastructure, agriculture, buildings) are more useful than measures of existing concentrations of pollutants — by revealing future environmental risks from loss or accumulation of stocks (eg. phosphorus) or leached heavy metals from corroding pipes. The degree to which total environmental loadings and sinks exceed the pre-settlement conditions indicate long-term or future impacts that are not yet anticipated. For example, half the manufactured fertiliser used in human history has been applied only since 1982, and the full effects of the accumulating nitrogen, phosphorus and potassium levels on human and environmental health are not yet known. Metabolic mapping can thus provide an early warning system for new environmental stressors (Brunner 1998).

Table 1. How MFA can contribute to other assessment tools

Environmental impact assessment (EIA) EIAs tend to limit choices to land-use options available when a proposal is put forward by development interests. They orient decision-making towards case-by-case approaches and incremental decision-making. They are often disempowering due to technical language.	**MFA** Unlike EIAs, MFA can deal with regional and cumulative impacts in a holistic framework. Metabolic maps (with GIS visualisation tools) can enable more meaningful citizen input. Note: see Table 5 for a complete description of how MFAs can contribute to EIAs.
Life cycle analysis (LCA) LCA is not an appropriate analytical tool for looking at the total impact of buildings and materials in an urban area (ie. cumulative impact assessment). It is a 'bottom up' approach that is highly complex and difficult to aggregate.	**MFA** MFA provides totals of energy and materials that can be attributed to buildings (on average). A 'top down' approach can save vast amounts of data processing and provide a cross reference to check bottom up approaches.
Embodied energy (EE) EE can identify inputs of energy but miss outputs of waste. For example, the embodied energy involved in the stages of car battery manufacture (mining, production and recycling) can be reduced, but this would not (in itself) reduce the amount going to landfill. Neither does EE look at where stocks of materials build up and their impacts.	**MFA** MFA can target better intervention points that bear the greatest dividends. For example, current regulations concentrate on CFCs in consumer products such as refrigerators. MFA results show there is a large stock of CFCs in construction materials which will be far more significant in the long term.
Genuine progress indicators (GPI) GPI are beginning to account for life-quality issues, but these indicators do not adequately address the role of the built environment and design in providing for greater environmental amenity at lower cost.	**MFA** Substantive life-quality improvements which satisfy basic social and emotional needs are essential in reducing consumerism (which is often a substitute for meaningful lives) and which can be achieved by design.
Environmental quality indicators (EQI) EQI and monitoring systems measure only the current state of the environment and generally focus on single issues or measurable environmental impacts in separate media (air, water, soil). Consequently, environmental policy has been in reaction to environmental stresses and tend toward solutions at point sources or single mediums.	**MFA** MFA can serve as a better indicator of a broader range of issues, such as resource transfers between media, to serve as a basis for triple bottom line accounting. It can also be used as a basis for a simplified set of indicators that measure fundamental system conditions. EQI are often not considered in their regional planning context, whereas MFA looks at links (stocks and flows) between broader systems.

2.5 MFA as a tool for planning sustainable futures

Integrated assessment models: Integrated assessment methods are generally used to generate information about alternative futures under various policies. These methods in NRM have thus far been limited in what they can achieve in an urban or regional planning context, because they are inescapably abstract, reductionist, positivistic and tied to projections of past trends. Even though integrated assessment modellers are concerned with developing methods that are inclusive of broad stakeholder involvement and transparency, transdisciplinarity and integration of social and physical sciences, adaptive management and other contemporary approaches (Jakeman and Letcher 2001), the models still reflect the narrow science paradigm of prediction, control and trade-offs, which contradict these stated objectives.

There is a conflict between the underlying assumptions and paradigms of optimisation modelling and designing positive futures. One can determine the resource requirements and waste and emissions of alternative futures, but models do not tell us how we want to live and

Table 2. How MFA can contribute to other sustainability frameworks

Conventional sustainability auditing frameworks	Potential contribution of MFA
State of environment (SoE) reports SoE reporting is necessarily retrospective. It needs to be brief and comprehensive, so SoEs cannot thoroughly analyse future scenarios. To date, SoE reports are a collection of virtually all collectable environmental information with a broad discussion of general implications for the future.	*MFA* MFA can create an early warning system of environmental hazards before they are measurable (eg. lead accumulation, toxins leaching into groundwater, nitrogen loading in groundwater). MFA can assist in analysing alternative options under different policies or strategies.
Urban metabolism (UE) UE in practice has focused on either demonstration projects (eg. urban village projects), or on the inputs and outputs of urban areas. The goal of increasing residential densities in cities has not been examined from a whole systems perspective.	*MFA* MFA enables a focus on the internal metabolism or the transformation of materials in an urban area, where systems design changes can often be the most cost effective. Cities can achieve self-sufficiency in ecosystem services if designed for sustainability.
Ecological footprint analysis (EF) EF has focused on equity between urban areas, but equity arguments are often lost by more compelling economic ones. EF describes the problem in a graphic way, but does not tell us how to fix it.	*MFA* MFA can show which materials are 'out of balance' with their bioregions. MFA enables more sophisticated analyses which link flows and stocks of materials to land use and carrying capacity, not just a generic or 'equivalent' land-use area.
Eco-efficiency Eco-efficiency has not gone much further than energy efficiency and 'cleaner production' programs. It does not focus on design of systems which cause the waste in the first place. It attempts to reduce waste at each step in production (eg. in the case of wood: timber extraction, processing, milling, manufacturing, transport and construction processes), but in practice seldom looks at the whole-system context.	*MFA* MFA focuses on systems design, not just minimisation of waste in production processes. For example, taking a wider systems view, 'woodless timbers' [ie. made from crops like bamboo, hemp or straw], could prove to be more eco-efficient overall than more efficient production of plantation timbers.
Industrial metabolism In practice, industrial metabolism has been largely concerned with developing networks of industries to create eco-efficiencies, or environmental management practices within factories. It has largely failed to address the need to reduce demand on industry for *more* products and throughput.	*MFA* In the absence of systems redesign, the 'rebound effect'' will reduce net efficiency gains unless total stocks and flows are taken into account. The rebound effect refers to the fact that a portion of the income saved through more efficient production is often spent on increased material consumption.
Scenario and least-cost planning Pathways to specific goals or more sustainable outcomes require the examination of the long-term consequences of alternative policies, plan, investments, land uses etc. Integrated assessment models do not reflect reality in cases where social and economic circumstances are in constant flux.	*MFA* Metabolic studies can provide a concrete basis for: (1) 'scenario planning' — which anticipates/predicts ends that will result from different options (means, politics, actions, land uses, investments). (2) 'least-cost planning' — which maps and compares alternatives means to achieve a desired end or goal.

how to get there. This requires a regional community design process (eco-governance); a crucial step on the pathway towards sustainability which tends to be overlooked. Our approach to optimisation modelling comes from a different direction: the promotion of the health of critical systems. This serves as a heuristic device which enables us to identify forces (stocks and flows) acting on a system, instead of the traditional emphasis on symptoms and their downstream impacts.

Scenario and least-cost planning: MFA can also contribute to scenario and least-cost planning methods. These methods are important strategic devices for regional governance, because pathways toward a sustainable society — defined through community design processes — require the analysis of alternatives and their long-term cumulative, regional impacts. Scenario planning tries to analyse the complex, multiple consequences of alternative futures, and least cost planning tries to determine the best means to a goal by backcasting. These processes are illustrated in Box 3.

Scenarios are often flawed because they do not include a whole-of-life analysis. For example, technology can reduce the emissions involved in the stages of car battery manufacture (mining, production and recycling), but it would not in itself reduce the amount of waste going to landfill. Similarly, current regulations concentrate on CFCs in consumer products such as refrigerators, but MFA results show there is a large stock of CFCs in construction materials which will have more significant impacts in the long term (Obernosterer and Brunner 1997).

Scenarios are often limited to two or three choices with a reduced number of variables for ease of comparison. In comparing timber use in construction to concrete and steel, for example, its far lower greenhouse emissions would seem to imply increased use of wood in construction (see Hendriks *et al.* 2000, p. 324). However, woodless timbers may be more eco-efficient overall. Further, woodless timbers would not be satisfactory in terms of greenhouse impacts without the use of solar heating, ventilating and cooling. Obernosterer *et al.* (1998, p. 64) provide another example:

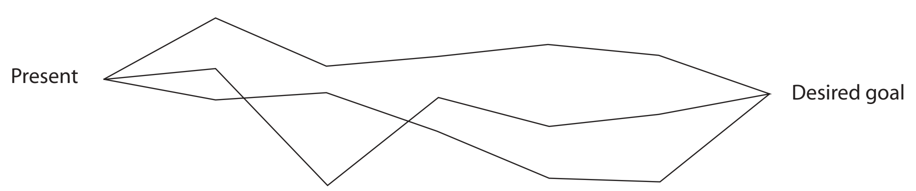
> Using today's demolition techniques such a policy could, when fully implemented, reduce the amount of construction waste flows (not including excavated soil) going to landfill by 45%. However, the recycling potential of construction waste could only reduce the current use of virgin materials of gravel and sand by 7%. In order to further reduce the use of virgin materials, alternative construction and planning approaches should be adopted such as focusing on higher density settlements. In comparison to Vienna, a project on the City of Zurich highlights that the recycling potential of construction waste could theoretically reduce the current use of virgin materials of gravel and sand use for buildings by 50%.

The above discussion shows that our approach to MFA can contribute to a wide range of conceptual frameworks and analytical methods.

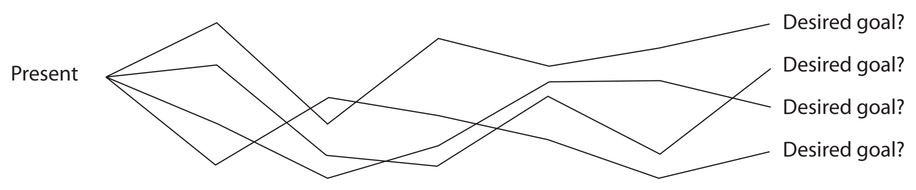
2.6 MFA as a tool for improving bioregional NRM

Bioregionalism has contributed insights, but has lacked a methodology that is consistent with those insights. As this is a very large area, the information is presented in tabular form (Table 3).

Box 3. Scenario and least-cost planning



Least-cost planning maps and compares alternatives (means, politics, actions, investments) to achieve a specific desired end or goal



Scenario planning anticipates/predicts ends that will result from alternatives (means, politics, actions, investments).

Table 3. MFA provides analysis to support a bioregional conceptual framework

Traditional planning and NRM	Bioregional planning and NRM	Material flows analysis (MFA) (regional sustainability audit)
Conception of human needs Human's needs were seen as best met by engineering solutions (eg. centralised energy, water, sewerage and transport infrastructure). Monetary costs prevailed over considerations of system-wide impacts and externalities.	Humans are seen as biological entities, subject to natural laws and limits. Humans and their cultures have co-evolved in response to their environments.	MFA assists in understanding the complex interdependencies of large-scale human systems in relation to each other and their bioregions.
Relationship of city to region Cities were seen as independent of the (social and ecological) region from which the urban area draws its resources. Natural conditions were seen as external threats (eg. slide areas, flood planes, health and fire hazards).	Cities and their economies are seen as integral parts of the natural bioregion. Low-impact dispersed settlement patterns for living that meet cultural, economic and physical needs are generally preferred over large cities.	MFA provides a systemic basis for linking flows between urban, industrial, and agricultural systems together in one system, and for determining optimal forms of urban development in different regions.
Urban–rural dualism An issue of growing social discontent in Australia is the linear flow of materials and wealth from rural to urban areas.	Economic as well as ecological sustainability requires that the city exist in a reciprocal relationship, or resource balance, with its hinterland.	MFA can raise the level of this debate and inform policy regarding resource allocation between rural and urban regions, by quantifying resource flows and wealth transfers.
Planning and NRM paradigms The protection of biodiversity and ecological processes (though now regarded as important policies) were not seen as requiring a fundamental re-orientation of planning paradigms and systems.	Participatory planning processes are seen as necessary to foster the ecologically based decision-making to support the complex ecosystems of the bioregion.	MFA provides new tools for analysis and mapping for communication to foster ecological literacy and improved decision-making.
Decision rules underlying planning and NRM processes In effect, planning processes were designed for choosing between land use or development proposals according to the highest economic use of land, using tools that are reflective of cost–benefit analysis (ie. to divide up resources instead of design for sustainability).	Inhabitants should determine their own decision rules, through bottom-up, participatory democracy, based on intimate knowledge of the local ecology.	MFA would assist public and private sectors in visualising the long-term implications of planning decisions and design solutions. It does not rely on the assumption that ecological awareness alone will lead to better decisions.
Role of the public in planning and NRM Consultation is seen as important for community ownership of principles and policies, but within a pre-established political framework. Volunteer practical self-help projects in regional Australia, such as revegetation programs, address local problems — but at a rate slower than processes of degradation, such as land clearing.	Importance is placed on cultural identity and identification with 'home' (bioregional landscape) or 'sense of place' of local residents. It is assumed that residents will care for an environment that they feel a part of, through active involvement in, for example, preparing resource inventories.	MFA goes beyond a reliance on behaviour and social change by focusing on the interaction and large-scale human-made systems, as well as local processes. MFA could be used to assess government program results, such as environmental education or Landcare, over which there is some debate about their value for money.
Limits to growth Conventions and methods did not actually acknowledge limits to growth, nor that the globe is one environmental system.	Attention is drawn to forms of trade or commerce that militate against regional self-sufficiency.	MFA has the potential capacity to deal with large-scale conditions and cumulative impacts — improved quality of life with less resources.

Table 3. (cont'd) MFA provides analysis to support a bioregional conceptual framework

Traditional planning and NRM	Bioregional planning and NRM	Material flows analysis (MFA) (regional sustainability audit)
Approach to revitalisation Regional/rural revitalisation was seen as requiring central government investment and problem solving.	A goal is be to become regionally self-sufficient in basic commodities by functioning within the limits of the carrying capacity of the bioregion.	MFA can determining the most ecologically-suitable urban, industrial or agricultural systems (eg. identify new light-manufacturing opportunities using agricultural waste) from local to national scales.
View of development Development was seen as means of economic growth — the goal — rather than the means of solving environmental problems. The design of development was seen as an unrelated issue.	Guidance is not provided for redesigning the built environment, except for advocating the use of local materials.	MFA shows how development itself can become a solution by reducing system-wide impacts with a financial return (eg. biobased building materials, resource autonomous buildings or retrofits and living machines).
End-of-pipe approaches Cleaner production and eco-efficiency approaches represent a form of end-of-pipe thinking that falls far short of eco-effectiveness.	Although working with natural processes is more important than assessing impacts, the focus is on environmental protection, not development.	MFA shows that the redesign of development can reduce extraction and production of raw materials for given ends.
Environmental management Tools largely only measure, monitor and mitigate impacts (ie. existing degradation and diminution). Minimising impacts at the site of extraction (forests, mines) and/or production (farms, factories) is essentially end-of-pipe.	While measuring is important in solving many kinds of problems, it is seen as less useful in issues requiring social and institutional change.	MFA provides guidance for scenarios and least-cost planning as a basis for evaluating the effectiveness of policy initiative and the design of future development.
Priority setting Priorities are set through formal policy-making processes. These tend to be in areas that have the greatest visible impacts.	The public decides priorities in a grass roots participatory process.	MFA assists in preparing regional sustainability audits and plans to guide development and ecological restoration.
Environmental justice Government programs promote on-ground action in repairing local environmental degradation (Landcare, Watercare, Coastcare, etc). The emphasis is on environmental awareness within an apolitical context.	Participation is intended to expand political awareness of the distribution of environmental benefits and burdens among different communities and social groups within the bioregion.	MFA provides a means of calculating the transfers of natural capital stocks out of the region in relation to resources flowing in (eg. distribution of benefits and burdens between and within regions).
Externalities NRM-related fields accept the economists notion of externalities (public costs of private economic activity) which remain invisible using conventional tools.	While largely understood, the problem of externalities has not been adequately communicated or resolved in the literature.	MFA makes externalities visible (eg. urban and agricultural run-off) by internalising these costs in the analysis.
Regional diversity Because land uses are mapped in separate zones, monocultural approaches to development planning are reinforced.	Permaculture, or small-scale integrated farming systems as opposed to monoculture, is advocated.	MFA can assist in comparing existing conditions to geogenic conditions to guide restoration ecology.

Table 3. (cont'd) MFA provides analysis to support a bioregional conceptual framework

Traditional planning and NRM	Bioregional planning and NRM	Material flows analysis (MFA) (regional sustainability audit)
Retrospective versus forward planning NRM has marginalised the design of the urban environment and has focused on indirect policy-making strategies (levers and pulleys).	Direct preventative design solutions by emphasising protection measures has tended to be overlooked.	MFA enables potential problems to be diagnosed and corrected by design before they become irreversible, providing early warning of pre-crisis environmental conditions (eg. build-up of toxins).
Carbohydrate economy NRM has focused on conventional resources and industrial processes. Land uses have been allocated and zoned in relation to the needs of a fossil fuel economy.	Land has not been inventoried for the potential *alternative* resources (biomass fuels, biobased materials for construction).	MFA can identify the carbohydrate sources that could lead to regional self-sufficiency (including fibre, energy, building materials and raw materials for industry).
Communication Geographic information systems (GIS) are slowly being integrated into NRM, as layers of spatial and time-based data to record changes in the spatial characteristics of resources within the region].	Work to combine GIS and bioregional planning is in the early stages in relation to soil types and vegetation cover. More has been done in biodiversity protection issues.	MFA can show causal links and chart future scenarios under different policies less expensively than GIS.

3 Specific methodological innovations

3.1 The problem of boundaries

A new approach to boundary definition is proposed which is designed to overcome two basic issues in the terms of reference: a) barriers to the implementation of bioregional planning; and b) problems associated with data collection and data reconciliation at the regional level.

A paradox in bioregional literature is the goal that common boundaries (though hierarchical, nested and sometimes overlapping) should be defined in terms of political, cultural and ecological features. Consequently, theoretical progress has stalled around a long-standing debate on how to define and establish such common boundaries, not to mention how to implement them. The fixation on trying to make boundaries of different kinds of human systems and ecosystems uniform (ie. merge governance, culture and ecology into one bioregion) stems from two contradictory visions within bioregional philosophy:

- the belief in the political or transformative value of community building and creating a sense of place — based on the notion that if people identify with a region they will understand, value and protect it
- the need to develop land uses and industries that fit the biophysical limitations of the region or catchment.

These goals present theoretical and practical difficulties that have been largely unresolved. There are at least two basic problems: 1) the connection between values, systems redesign and implementation is weak (ie. new values do not change paradigms and methods; 2) technical and structural support is required to design appropriate development (that supports ecosystem services and life support systems). Appropriate regional planning methods cannot be developed unless the concept of boundaries is consistent with ecological realities (Birkeland 2002).

The above two inconsistencies relate to the traditional idea that regions should be divided horizontally and vertically:

Uniform (geographic) boundaries

Defining regional boundaries by geographical land-use characteristics is problematic because it entrenches a dated if not misleading view of nature. Natural systems are dynamic and interconnected. There are fundamental differences between amorphous interacting natural systems and rigid human-constructed institutional structures. On the one hand, natural systems are adaptive, self-organising entities, whose boundaries are constantly shifting (eg. rivers move, climates change, species adapt), and all these entities are affected by a range of different forces. One the other hand, boundaries are necessary for administrative purposes, which result in rule-based and regulated management systems.

Also, administrative boundaries, because they are tied to and affect power relationships, are difficult to change. This has been a barrier to the implementation of regional planning. New political boundaries, while helpful in some cases (eg. where river systems fall within two or more jurisdictions), would not totally resolve the issues. Shifts of political power, a sense of place, pride in community 'ownership', and even the ability to control upstream influences, will not untangle the paradigmatic legacies of environmental management. For example, the development of resource options has been based on past requirements of a fossil-fuel based economy, rather than looking at more benign resource development options; that is, land-use planning has used zoning as a tool which, in turn, has shaped thinking about land use. These land-use zones have been tailored to the needs of an industrial age and have, in turn, worked to entrench industrial age solutions, when ecologically based whole systems solutions are needed.

Global and local scale issues

It is also problematic to separate environmental boundaries vertically as they are interconnected on all levels — microscopic to stratospheric. Thinking in terms of nested regions at difference scales (georegions, ecoregions, bioregions, etc.) does not give adequate recognition to the influence of large-scale global forces, such as climate change, and how global climatic forces interact with local topographical and microclimatic variations (ie. natural phenomena are more like Chinese puzzles than Russian dolls).

Rather than trying to make nature fit concepts, then, we should adapt metabolic mapping to the idea of mutually interacting, fluid, non-hierarchical boundaries.

MFA boundaries

MFA boundaries have previously been set in one or other of two ways:

1. through the identification of chains of processes that are necessary to meet human needs
2. through the division of a system into its main processes, such as anthroposphere, atmosphere, hydrosphere and pedosphere. (Baccini and Brunner 1991)

A third way is proposed here: mapping critical systems separately (eg. water, energy, asbestos, erosion, salt), without regard to boundaries, and overlaying them to identify interrelationships. The most fundamental limiting systems in the region should be mapped first, to examine the overlays, conflicts and potential synergies affecting these key entities. This is not to replace other forms of boundaries, but to provide an alternative view for heuristic purposes. We can call this new approach 'organic mapping', as opposed to 'process mapping' or traditional 'hierarchical mapping'.

This simplification has several advantages. It would, for example:

- *Re-orient thinking towards system health:* In this organic view, environmental management may become more proactive. Rather than measuring environmental stocks and flows of whole regions, it would focus on enhancing each critical natural system's capacity for self-organisation within the constraints of needs and parameters created by countervailing biotic and abiotic systems. Each system could have a public body looking after it. In the short term, task forces, ombudsmen, or commissions, 'friends of' rivers (forests, soils, etc) have made a difference where they have focused on an organic entity. This approach to mapping critical systems readily aligns with existing administrative models, such as the Murray–Darling or Columbia River agencies. Organic mapping could be used by such agencies or other groups as a diagnostic tool.
- *Solve most data collection problems:* It is easier to obtain data relevant to the particular ecosystem, rather than according to new geographic boundaries. This applies to the key materials either being examined, or to be examined, in this study: water, energy and wood.
- *Focus on eco-solutions:* MFA enables analysts to identify weak points in these fixed and fundamental limiting systems at the regional level and seek creative solutions. For example, in Australia, where salinisation of both land and waterways is a big problem, salt can be drawn off fields to be used in dying (colouring) materials, or salt lakes can be used to produce solar heat, grow brine shrimp, and so on. That is, uses can be found for salt that removes it from the land.
- *Improve community awareness:* Eco-innovations themselves have an awareness-raising value as demonstrations of 'ecological design' solutions that improve the health of primary ecological systems while improving the economy. This can be as educational as learning to empathise with one's region. The final selection of metabolic maps will need to establish limits on the amount of data presented if it is to communicate information in a useful way (because, for example, tracing embodied energy upstream through several levels will involve problems of 'complex systems').

3.2 Data gaps at the regional level

Data gaps are greatest where data are most needed for effective NRM — at the regional level. Therefore, we initially assumed that barriers to the implementation of bioregional analysis included:

- *the lack of existing data:* In the event, there were vast amounts of data, but by looking at data pertaining to key systems (as opposed to compiling and measuring impacts in a region), we discovered major inconsistencies in existing data.
- *the difficulty of aligning data with regional boundaries:* By looking at critical systems as entities (such as soil, water, wood), we found that data from different sources did not add up (see below). A good example of this is that, by mapping salt flows, a colleague has discovered that salt does not behave the way that specialist researchers have previously assumed. For example, there is some evidence that salt activated by the Murrumbidgee Irrigation Area (MIA) is moving through ancient underground river courses in the Lachlan catchment.

The real problem, then, is *neither* a lack of data or relevant information, *nor* the difficulty of reconciling this information with regional boundaries. Instead, it is the failure to modify the traditional concept of boundaries to match the need for systems design (in lieu of monitoring nature's resilience).

By changing the concept of geographical boundaries, in both MFA and bioregional planning, we can eliminate the following 'problems' (for immediate purposes) that we had previously identified. These previous problems were:

1. there is little information to link material consumption with environmental impacts, because industries tend to collect and hold data concerning production sites and operations, not product lines;
2. there are gaps in information about flows and stocks of specific substances in official statistics, and these vary from place to place;
3. 'hidden' (or 'rucksack') flows have not been reported in official data. [These are materials that do not enter the economy, such as earth moved in construction, mining overburden, or soil erosion (and represent about 70% of the total material flows in Australia if water and atmospheric flows are excluded)];
4. freshwater flows and atmospheric flows tend to be so large that they dwarf other data, yet are crucial issues in Australia in particular;
5. statistics focus on goods with economic value, rather than on the substances that are aggregated within such goods (or hidden flows that have no commercial value);
6. wastewater discharge from most buildings are not metered, and the sectoral sources of wastewater arriving at treatment plants are not identified;
7. few data are available on the amount of asbestos in buildings, or the amount removed each year, as is also the case with many other hazardous substances;
8. waste generation impacts are not yet quantified in terms of product life cycles;
9. residuals from industrial processes are complex and their impacts vary according to the medium in which they are carried;
10. there are few available data on material stocks recovered for reuse in industrial, domestic and commercial sectors.

In short, rather than trying to collect data on anything that is measurable, we begin by establishing a framework to determine what we should be measuring. Our conceptual framework begins with a fundamental systems view.

3.3 Reconciling conflicting data

MFA as a true audit

Simply by providing a new framework for generating environmental data, the new MFA model can uncover gaps and inconsistencies in data. In this way, it can provide a true 'audit': that is, it can reconcile input and output measures from many different sources.

Water: Almost every figure obtained through existing sources on water is contentious, as different agencies use different assumptions, measures, sampling regimes, modes of handling seasonal or decal variations and so forth. Informal discussions with individual officers responsible for taking measurements tell us that many of their returns are at best 'guestimates' (to quote an officer: "if it is too wet to go out when a measurement is due for example, we sometimes estimate the flow on the basis of reported — not locally measured — rainfall"). There are enough discrepancies in water data to cast doubt on the accuracy of uncritical, non-reconciled 'stocktake' approaches practised by the numerous water authorities.

Energy: There are numerous data sources for energy, but since the privatisation of electricity supplies, there are fewer data available than previously. Household expenditure data can be used to calculate total consumption (we refer to this as 'derived data') and seek to reconcile this with data available through other sources ('published data'). As with water, inconsistencies are emerging with energy data, to the extent that it brings the value of energy as a unitary concept into question.

Wood: Analysis of wood, using MFA, is uncovering discrepancies in this area as well. Wood data themselves are also problematic on more scientific grounds. Typical plants (when dry) contain a relatively constant proportion (35–50%) of carbon (Atwell *et al.* 1999, p. 161) and plant physiologists know about the rate of uptake of carbon, water and nutrient by plants under laboratory conditions, but this is typically based on very small-scale research (eg. work done on the efficiency of photosynthesis is done on individual leaves). The results are then scaled up to estimate the efficiency of carbon fixing in whole plants, then trees, then forests (including rainforests) and ultimately the whole planet.

These scaled up data are used in estimating greenhouse absorption rates, carbon sinks and so on. According to Professor C.B. Osmond, director of the Phoenix Biosphere Project, preliminary work is already indicating that much of the early scaled up modelling is *incorrect* (pers. comm.) and plant–environment interactions are much more complex than generally recognised. The Phoenix Biosphere (in Arizona, USA) is now being used to undertake large-scale (whole system) studies on plant performance. Other research indicates that biodiverse planting areas absorb more carbon than monocultures, and more carbon is stored in forest floor than in trees (which have a shorter carbon cycle).

Data consistency: The lack of consistency of reliable data is a notable feature of data generated by the plethora of authorities. One cause of such inconsistency relates to diverse approaches generated by disciplinary approaches underlying NRM. For example, eutrophication of waterways is attributed in part to excess nutrient run-off. Other models suggest our nutrient-poor soils justify the import of additional nutrients. Consumers are encouraged to avoid detergents high in phosphorus even though by far the major source of phosphorus (over 80%) is from soil erosion. The contribution from detergents is so small it is barely measurable, and so on.

Our transdisciplinary research is showing that every problem area is caused at least in part by every other. This is illustrated in Diagram 7 (Appendix, p. 65), which sets out the causal links found in the literature between various well-documented problem areas: salinity, erosion, irrigation, nutrient and biodiversity loss, etc. The literature offers empirical support and explanations for these links. The general explanation for this is "European farming methods". But while this has some value in drawing attention to the problem, it does nothing towards a solution.

To judge data quality in an MFA context, agencies will need to be asked to account for the discrepancies in their published data (assumptions, aggregation methods, phasing, sampling and collecting methods, etc.). Only when their responses have been analysed would we be in a position to make judgments about data quality. There appear to be far more discrepancies in this region of Australia than one would have expected. Other areas need to be tested to see if similar discrepancies exist elsewhere.

3.4 Simplifying the complexity of human–environment relationships

As mentioned, simulation and integrated assessment models are concerned with the performance of the environment to cope with stresses or to predict natural disasters — rather than on the development of new technologies and management systems to enable humans to live within their means. Complex models that seek to replicate natural systems may never achieve adequate reliability, because of the unpredictability of social interventions. Modelling in planning fields has never achieved whole-systems analyses and is often limited to specific functions like transportation. This means assumptions can easily be overly reductionist, and errors can be magnified out of proportion.

It is important to identify and examine the most critical substances and materials to Australia's urban and rural environment, and key internal processes where materials are transformed. Our approach is to simplify the key variables to be addressed by the model without ignoring the complex network of forces acting on a system. A stocks and flows approach provides a framework for simplifying the work involved in maintaining and updating such lists and measurements.

3.5 Conceptual framework

Eco-development C&I requires that fundamental systems dynamics are not overlooked, and that measurements are linked to systems health, not just symptoms. Therefore, a conceptual framework was developed as a basis for determining specific C&I and implementation strategies. While most EQI and USI involve dozens of items to measure and monitor, this model starts with only three for development — ecosystem services, material renewability/reusability, and resource autonomy (municipalities can add others). These focus on fundamental dimensions of the built environment — open space, materials, and environmental performance. However, basic planning and land-use decision-making should begin at the bioregional level; the development indicators are integrated into a regional framework (Table 4).

3.5.1 Nature/ecology/region

Fundamental measures of ecological sustainability

1a) Carrying capacity: When defined as the set of (ecological/economic) functions or environmental load that the bioregion can support, the carrying capacity of virtually all bioregions surrounding urban areas has been

Table 4. Conceptual framework overview

Sustainability	C&I relating to fundamental systems	Key strategies
1. Nature/ecology/region	a) Carrying capacity b) Biodiversity	• Sustainable landscape (eg. habitat diversity, permaculture principles) • Nature corridors • Enhance soil structure
2. Ecologically sustainable development	a) Eco-efficiency • Dematerialisation, b) Healthy buildings • Detoxification, • Decarbonisation	• Ecosystem services • Resource autonomy • Renewable/reusable materials (bio-based production/ (healthy materials)
3. Social/wellbeing/economy	a) Genuine progress b) Environmental space per person	• Human resources (job quality Capacity building) • Internalisation of costs • Eco-factor

exceeded (in fact, the ecological footprint of urban areas can be 200 times the area that the city physically occupies). This is a complex issue, having conflicting interpretations in different fields. (As technology becomes more eco-efficient, carrying capacity can increase, but generally technology has only camouflaged the ecological crisis.) Unlike the ecological footprint concept, the carrying capacity depends upon the biophysical characteristics of a specific site.

1b) Biodiversity: Biodiversity is a fundamental indicator of ecological resilience. Biodiversity provides the system resilience that is lost through monocultural development. *Our research indicates that it is possible, through ecological design, to maintain ecosystem services in urban areas in a manner that preserves or enhances urban biodiversity.* Practical indicators and measures that represent leverage points for improving biodiversity need to be identified.

Key strategies for increasing carrying capacity and biodiversity

- **Sustainable landscaping principles:** The landscapes of development sites and whole regions are the matrix within which the structures and processes of the production/construction/agriculture systems takes shape. Australian governments have recognised that ‘imported’ agricultural systems are not well suited to the unique Australian habitats and have begun searching for means to achieve sustainable landscapes. Permaculture is one design philosophy which provides some guidance for achieving sustainable landscapes by designing the connections between components of a system.
- **Nature corridors:** It is not simply the total area set aside for ecosystem services in urban and rural areas that is important, but the way in which open space is integrated with, and separated from, developed areas in the region. To reduce the impacts of habitat destruction, nature corridors (comprised of local native species) should be linked together around ‘islands’ of development — as opposed to trying to maintain islands of nature in a sea of development.
- **Soil structure:** All life depends on soil (as well as water), which is being polluted, concreted over and eroded away at alarming rates. Our research indicates that soil structure is a core issue linking major Australian environmental problems: loss of soil productivity, increased run-off and erosion, leakage to groundwater, salinity, eutrophication of waterways, and loss of biodiversity. This is illustrated in Diagram 8 (Appendix, p.66).
- Soil serves as an ecological sponge of below-ground biotic activity which soaks up water and thus addresses many of these problems. Soil enhancement strategies have not yet been applied in any systematic and rigorous way. It may be possible to maintain and enhance soil structure by returning organic matter to soils, and increasing microbial activity *in situ*. This can be done at very little or no additional cost, as the savings in chemical fertilisers and urban-waste management will provide a substantial offset (in Australia, waste-management systems destroy organic matter or pump it out to sea at costs of over $4 billion per annum, while farmers are simultaneously paying more than $2.5 billion at the farm gate for chemical fertilisers).

3.5.2 Ecologically sustainable development

Fundamental measures of ecologically sustainable development

2a) Infrastructure efficiency measures whole systems costs (material stocks and flows) involved in the built environment and transport of people, water and energy. Infrastructure here includes the built environment and capital stocks, their externality costs and efficiency (eg. greenhouse gases emitted per square metre of buildings). Conventional monetary-based measures, such as cost to the driver or cost per mile, conceal externalities and perverse subsidies.

- **Dematerialisation:** Dematerialisation is the reduction in the materials and energy intensity in buildings to achieve the same or greater functions. It should be achieved simultaneously with a transition away from fossil-fuel (petrochemical) consumption (ie. decarbonisation).

2b) Health of environment and people

- **Decarbonisation:** The transition away from fossil-fuel (petrochemical) consumption in materials (textiles and construction) and fuels (heating and transport) are essential means of achieving ‘decarbonisation’ (using less carbon over time to achieve a given output) by using renewable bio-based fuels. Improved public transport and reduced car dependency are well recognised as important components of sustainability, as they would result in dematerialisation, decarbonisation and detoxification. However, the greatest barrier to decarbonisation is the hidden subsidies to private transport: thus the internalisation of real costs is essential.
- **Detoxification:** One third of new buildings generate complaints of sick building syndrome. Substances that do not occur in nature and are not readily absorbed by the natural processes should be avoided — especially if they are toxic, like some materials used in paints and surface finishes. Renewable and bio-based materials (ie. those made from plant materials and without fossil fuels) also reduce harmful particulates being released into the environment during use or demolition.

Key strategies for achieving eco-efficiency (dematerialisation) and a healthy infrastructure (decarbonisation and detoxification)

2a) Urban ecosystem services: Every economy is totally dependent on ecosystem services, such as the availability of clean air and water, and fertile and good quality soils. These include direct economic benefits as well, such as recreational and aesthetic benefits. It is now recognised that most ecosystem services cannot feasibly be replaced by engineered systems.

Urban development is sustainable where the development maintains or increases the pre-development level of ecosystem services. This is partly achieved by limiting impervious surfaces to a specific proportion of the block, and/or increasing the proportion of urban open space through design (eg. decks or roof gardens). Where insufficient open space is left, additional rates could meet the cost of providing ecosystem services elsewhere. This would counter existing biases against open space protection, such as traditional valuation (eg. 'highest economic use') and density measures (eg. 'dwellings per hectare').

2b) Resource autonomy refers to a development's operational performance in terms of its independence from off-site supplies of lighting, energy, soil, sewage and water treatment. Development can also provide good indoor air quality (many materials emit volatile organic compounds and other health hazards). That is, resource autonomous development aims for buildings that physically internalise or avoid development impacts. Examples of both new and retrofitted homes that have achieved resource autonomy exist, but are not widely recognised.

2c) Material renewability/reusability is the total materials and embodied energy in buildings in relation to their economic life expectancy. Ideally, all components would be completely renewable (compostable) or at least reusable in their current form (ie. bricks reused as brick, not as road material). Where possible, any materials should be locally produced to reduce transport energy.

- 'Reusable' here means that the material is to be used another time for the same purpose as originally manufactured. Reusable, natural and long-lasting materials (such as stone), should be used in high wear areas. Where reusable non-biotic materials are required, they should be applied in ways that allow disassembly (eg. bricks or steel components if designed for disassembly).
- 'Recyclable' materials typically entail high levels of embodied energy and should therefore be avoided.

3.5.3 Social/wellbeing/economy

Fundamental measures of equity and well-being

3a) Genuine progress indicator (GPI) represents an attempt by ecological economists to replace GDP with a standardised set of indicators of wellbeing. Although it is becoming widely accepted that 'triple bottom line' accounting means that development must be equitable and focused on human wellbeing (rather than material consumption) GDP has had the opposite result. For example, it does not distinguish between activities in the market that are good for the environment and those that cause harm (eg. the Exxon Valdez oil spill increased GDP), and this does not count things outside the market (eg. volunteer work, ecosystem services). However, GPI is complex, and needs to be simplified for use in development assessment.

3b) Environmental space is the total amount of energy and resources (including land, water and forests) that can be used sustainably, divided by the global population. Hence, it serves as a measure of the fair share of resource usage and distribution based on actual measurements of resources, emissions and space. (This differs from measuring ecological footprints, which translate the resources needed to support a population, group or city, taken from around the world, to the 'equivalent' area of land and water at that location.) It enables comparisons of per capita consumption to be made between different regions and nations.

Key strategies for achieving equity and wellbeing in development

- **Internalisation of costs:** If people are to make informed choices, they need to be aware of the impacts of their decisions. Thus, internalising the actual costs and benefits of development — or at least making externalities and subsidies transparent and explicit — is essential in achieving sustainable development. For example, from a whole-systems perspective that takes all externality costs and benefits into account, public transport saves energy, resources, and increases public health and safety. Planning in the last decade, however, has been preoccupied with increasing residential density (eg. dwellings per hectare) to discourage car usage to, in turn, reduce energy use and greenhouse gas emissions. This is an indirect, costly and uncertain way to support public transport because 'accessibility' to public transport through zoning and land-use planning, though important, is not nearly sufficient to overcome the 'hidden' subsidies favouring car ownership and usage.
- **Human resources (jobs and capacity building):** When development proposals are supported by claims of job creation, the debate often ignores the opportunity costs and quality of these jobs. A

shorthand for GPI in assessing development proposals may be the relative cost of the jobs created, the nature of the work, the social displacement entailed by a project, and alternative ways of creating jobs. Jobs in design and construction are skilled and low-cost in relation to financial dividends. Similarly, the development of human resource potential, an essential component of sustainability, is often omitted in the assessment of project proposals. Capacity building increases the ability of local individuals to design for sustainability or engage in green business enterprises that improve environmental conditions in a sustainable way (ie. self-funded or profitable).

- **Ecofactor:** One means of internalising environmental costs in planning tools is to use the eco-factor (Cocks 1992). The eco-factor is the opposite of the economists' 'discount rate'. The discount rate used in benefit–cost analysis is based on the idea that money today is worth more than money tomorrow. Consequently, it devalues the environment over time. However, the natural environment is decreasing while appreciation of its intrinsic value is increasing. An eco-factor would internalise the increasing value of the environment into development decisions.

3.6 Improvements over other assessment tools

Simplifying impact assessment and system boundaries

Environmental-impact assessment (EIA) is a project-assessment process for drawing decision-makers' attention to environmental risks. It was not designed to prevent environmentally damaging projects. However, the process can lead to conditions being placed on the development approval which save resources and money (for example, more-energy-efficient design, cleaner technology, or even a better location for the project). In practice, improvements to projects are marginal. Further, the time and costs involved in preparing EIAs can create an undue burden on developers in relation to public benefits gained (ie. the benefit–cost ratio of the EIA process may not be satisfactory).

Two issues that have plagued impact assessments are determining (upstream and downstream) systems boundaries for purposes of performing cumulative and/or regional assessments. Our new approach to MFA can address both problems:

1. by reducing the number of things to measure and therefore the number of upstream and downstream complexities to trace
2. by being simpler, with fewer measurements, facilitating the preliminary EIA process, saving monetary and human resources.

Simplifying environmental indicators

Environmental quality indicators (EQI) measure physical, chemical, biological or socio-economic phenomena to obtain information that reflects changes in the condition of ecosystems, human health and life-quality generally. Their main purpose is to provide guidance on policy priorities but, in practice, much time and resources go into measuring and monitoring indicators of environmental conditions. The result is that institutional decision-makers do not generally use EQI in daily decision-making at any level. There are many (potential and actual) shortcomings of EQI that need to be avoided.

Table 6 suggests how the new MFA approach can overcome many of these problems.

Table 5. Problems with EIAs addressed

Some problems of EIA to be avoided:	Ways the new model can overcome this:
Many large-scale infrastructure and development decisions made in the private sector are sometimes not subject to EIAs or otherwise can escape assessment.	MFA is potentially simpler, to enable wider application. MFA maps would provide a starting point for evaluating land use proposals.
The EIA is usually separate from (or even occurs after) the design process, but the impact depends on the choice of materials, layout, processes and components etc.	MFA can be useful at the site-planning and design stage. MFA is proactive and focuses on basics.
A number of projects that appear individually benign can have significant cumulative and regional impacts.	MFA can assess projects as part of a revised land-use plan for the region.
EIAs do not facilitate 'scenario planning' (which analyses the consequences of alternative futures).	MFA facilitates scenario planning and least-cost planning.
The EIA is prepared by the proponents; accountability is enhanced where an independent assessments can be conducted.	MFA would be public information and the changes to be brought about by a proposed project would be easy to model.
EIAs sometimes identify a narrow range of alternative developments and do not determine the best use of land.	MFA can be used to help determine the best use of land.
There is a bias against the 'no development' option, which seldom creates jobs, as the benefits of ecosystem services are not valued.	MFA can place a value on ecosystem services by including natural stocks and flows.
Under the present EIA process, the decision is often perceived as a simple 'yes' or 'no' issue, for example, 'to dam or not to dam'.	MFA is proactive and provides design guidance.
EIAs begin with a developer ready to invest in a specific project. A developer proposing to build a centralised energy production system will not be prepared to examine decentralised energy structures.	MFA can compare existing conditions to the endogenous condition.
EIAs tend to count the number of jobs — not the quality of jobs. For example, dam construction appears to create more jobs than the 'no dam' alternative.	MFA enables job quality to be evaluated. MFA Jobs created through MFA analysis (ie. eco-efficient) would make a positive ecological contribution.
The EIA process does not weigh social impacts or community-building activity.	MFA looks at human-resources implications.
EIAs tend not to look at cradle-to-cradle factors and/or long-term public costs (eg. cumulative pollution, medical bills, lost options, clean-up costs, and other externalities seem too remote and uncertain).	MFA can identify flows through time and space. In addition, MFA indicators are cumulative. Long-term costs can be assessed more readily than by using impact assessment.
Even when indirect and remote impacts are considered, such as effects on future generations, these are 'discounted', or reduced to current values.	MFA (or EIA) can include an accounting for long-term impacts (eg. ecological factor).
A project is seldom monitored for compliance. Assumptions and claims are not always verified later.	MFA eco-development criteria and indicators (C&I) are both a design and performance/monitoring tool.
Unforeseen environmental effects can be deemed 'approved' when the building permit is issued.	MFA can be independently assessed.
The technical nature of the EIA can be intimidating to lay people, such that what is represented to be a participatory process can be obfuscatory.	MFA can avoid the focus on the adequacy of the process or procedures followed, and place more emphasis on the merits of a development. It is more comprehensible for lay people.
EIAs do not consider distributional aspects (eg. areas with low pollution, such as farm land, are likely prospects for industry location due to ambient air quality well above minimum standards (leaving more room for pollution)).	MFA includes equity (environmental space) impacts. Makes visible how poor people tend to bear the costs of development.
Many projects could not stand on their own financially without these publicly-provided benefits such as the existing infrastructure of roads, grants, tax shelters, and low-cost loans.	MFA can incorporate the concept of reciprocal benefits for the local community in planning and design, and make these resource flows visible.

Table 6. Problems with EQIs addressed

Some problems of EQI to be avoided are:	**Ways new MFA model can do this:**
Planning and development decisions are often not considered in a regional planning context.	MFA looks at links between major regional systems.
EQI are expensive to develop, because they need to be comprehensive. They are often unwieldy, and easily forgotten in day-to-day decision making.	Assessing the effect of new development proposals in major regional systems is simpler than measuring all (disaggregated) impacts.
They generally measure only the current state of the environment and indicate only whether specific measurements have improved or not over time.	By focusing on the health of basic systems (versus a diverse set of numbers), MFA can convey how serious existing conditions are.
EQI tend to measure problems only after they are manifested as environmental stresses, rather than providing an early-warning system.	MFA measures increases in stocks of substances before they have visible impacts.
They are not linked with budgetary systems, priorities and timetables of relevant actors in governments and businesses.	MFA could readily be linked to government policy and business planning processes.
EQI have not been integrated adequately into management plans at levels such as farm plans, catchment plans and local council plans.	MFA is designed to be a powerful management planning tool.
They do not indicate environmental services lost (or possible but for the adverse impacts).	MFA looks at all environmental services.
EQI tend not to reflect all the 'real' costs of using the environment as the natural base for production.	MFA looks at externalities and wealth transfers in and out of regions.
Costs to the public (externalities) seem small compared to the (relatively) high costs falling on individual stakeholders.	MFA shows real costs to the public of wealth transfers instead of price.
EQI tend to focus on single issues or measurable environmental impacts in separate media (air, soil, water).	MFA looks at whole systems in terms of basic stocks and flows (instead of arbitrarily bounded entities).
They encourage responses that focus on fixes at point sources or in single media.	MFA looks at system-wide stocks and flows (versus stock takes).
EQI are embedded in frameworks that tend to obscure the complexity of casual links in terms of whole systems.	MFA can direct public investment towards systems solutions and not just immediate causes.
They focus on the capacity of the environment to respond to human actions (eg. environmental resilience).	MFA can shift focus to the performance of human environmental management systems.
EQI are generally not designed to increase accountability in decision-making, nor even avoid the need for appeals etc.	MFA can make managers more accountable for system change.

4 Progress: data, findings and applications

This section outlines our initial findings for water, energy and wood, and presents our approach to collecting, collating and presenting this information. It also introduces some new applications for the proposed approach of mapping separate stocks and flows by their own boundaries (eg. whole-water systems) instead of by regional boundaries.

The main substances studied using MFA were wood, water and energy. As explained below, since wood is a complex of materials, we have instead used two indicative elements: carbon and phosphorus. Also, we have added soil structure as a key integrating issue and as a leverage point for addressing a majority of threats to sustainable agriculture in Australia.

4.1 Data

Water: The amount of data available are formidable. In addition to the data sources used in the National Land and Water Resources Audit (NLWRA), we have looked at a number of water flows and quality measurements in the Australian Capital Region (ACR) undertaken by various authorities funded by the NSW, ACT and Federal governments. When these sources are mapped in a systematic way, using MFA, inconsistencies in the data become manifest. There are enough inconsistencies to cast some doubt on the accuracy of uncritical, non-reconciled aggregations or 'stocktake' approaches practised by the numerous water authorities in this country. Diagram 1 (see Appendix, p. 50), along with its explanatory notes, gives a first draft mapping of water flows for the ACT. These data still need to be thoroughly checked and analysed, but they serve to illustrate that, by applying MFA to whole river systems, we can audit accounts and reconcile conflicting data.

Energy: As with water, there are numerous data sources for energy, but since the privatisation of electricity supplies, there are now fewer data publicly available. Household expenditure data are being used to calculate total consumption ('derived data') and seek to reconcile this with data available through other sources ('published data'). At this stage, an MFA approach to energy reveals inconsistencies so great that it brings the value of energy as a unitary concept into question.

The literature treats energy as somewhat analogous to water in that it is seen to 'flow' from one type to another (eg. from coal to steam to electricity) with losses at each transformation. Like water, some energy sources can be seen as stocks (wood, coal, oil etc.); however, unlike water, electricity is not easy to store. Thus, electricity stocks need to be seen in terms of the weight of materials from which the electricity is generated.

Due to the profound environmental implications of different energy sources, we have considered each separately. Thus, the environmental impacts of each energy mode (coal, gas, photovoltaics, biomass etc.) are examined as if we depended solely on each. This gives a basis for a matrix upon which to design a more-sustainable mix at a local level. For example, areas with high wind and low sunshine would have a different mix from areas with high sunshine and low wind.

Diagrams 2 and 3 set out conceptual energy flows for the natural and built environments, respectively. These diagrams, based on Boyden (1994), have been simplified to make them more useful as communication tools.

In our report to ACT Planning and Land Management (PALM) (which focused on urban development) the building sector was seen as the greatest consumer of energy, even greater than transport. However, this is unlikely to be the case for whole regions, where transport is almost certainly the largest consumer of energy. Transport systems readily lend themselves to MFA mapping in terms of the material, goods, or people transported. Nevertheless, more work needs to be done on the relationships between energy movement and transport systems. They are by no means isomorphic and will probably require separate mappings.

There are serious problems of categorisation in the energy area. For example, the ACT and indeed the whole ACR, does not generate its own electricity (predominantly buying it from NSW). Under international rules, greenhouse gas emissions in the ACR are attributable to NSW, not the ACR. However, the ACT greenhouse strategy accepts responsibility for NSW emissions for electricity sold into the ACT, even though it has no responsibility or control over the source of the energy.

Wood: Mapping the stocks and flows of wood in the ACR also involves anomalies. While there are many data available, precise definition of, and information on, the amounts of wood in all its various forms is lacking. Obvious categories include firewood, sawlogs, and woodchips, but the data include fresh logs/chips (which contain a large proportion of water) and also veneers, particle boards, paper and a whole range of products using wood and such wood fibre substitutes as cane, straw, bamboo etc. While wood may be a major constituent of these products, they also include a substantial proportion of adhesives, fillers, stabilisers, antifungal agents and other chemicals. Therefore, it has been necessary to divide wood into its key constituent elements.

4.2 Wood components

To avoid definitional and constituency problems, the functional role of plants in natural systems has been used in this study to derive more meaningful categories to analyse and map. The elements carbon (C) and phosphorus (P) were selected for this purpose; along with water, they are essential to all living organisms. These elements also play a central role in agricultural, transport and energy systems. They are central to the great debates on climate change and the application of European farming techniques in an Australian context. Before presenting MFA data on these elements, some background information is provided to justify their selection.

Plants: Almost without exception, plants are the only productive units on earth. Other living organisms are directly or indirectly consumers of plants. The unique productive capacity of plants derives from their ability to photosynthesise: the process of using energy from the sun to turn a relatively small number of simple elements and compounds into vastly more complex proteins, carbohydrates and so forth that make up the building blocks of all living organisms. The only known exception consists of a recently discovered group of organisms that derive their energy from chemical sources along deep-sea vents. (Several billion years ago, the ancestors of these organisms produced the atmospheric oxygen and carbon dioxide that made other life possible.)

Water is the principal constituent of plants; about 90% of their fresh, live weight (Singer and Munns 1992, p. 200). When dry, typical plants contain a relatively constant proportion (35–50%) of carbon (Atwell *et al.* 1999, p. 161).

Sixteen elements have been shown to be generally essential to plants:

macronutients – C, O, H, N, K, Ca, Mg, P, S

micronutrients – Fe, Mn, Zn, Cu, Mo, Cl, B

Every cell of a plant seems to need each essential element, though different cells are particularly rich in some. For example, the growing parts and fruiting bodies of plants are particularly rich in phosphorus, but the stems and trunks, when no longer growing, are relatively poor in phosphorus. Thus, in the case of agro-forestry, if only trunks are harvested and the leaves, roots and fruiting bodies are allowed to decompose *in situ*, relatively little of the nutrients is lost. In the case of grain crops, however, the seeds are harvested and the stems and roots are allowed to decompose, effectively removing a greater proportion of the available nutrients. These facts are very important in designing truly sustainable agriculture systems. For example, sugar is one of the ‘purest’ products produced. It consists solely of hydrogen, carbon and oxygen. The sugar industry could be sustainable if all the bagasse and ‘impurities’ from the refining process could be returned to the soil. There would be costs associated with this, but these would be offset by eliminating the need for fertilisers. In Australia, nutrient-rich run-off is one of the factors threatening the Great Barrier Reef.

As plants are sedentary, all nutrients need to be within a plant’s reach if it is to survive. Herbivores and human activities that remove plant material can only do so sustainably as long as there are systems in place that return these nutrients to where plants can access them. As is well known, natural ecosystems do this and self-regulate to maintain these flows. For example, nutrients are brought to plants through the atmosphere (in the case of carbon dioxide and wind blown dust), water for soluble nutrients and the decomposition of rock through weathering and the activities of some plant roots and other organisms. The challenge for NRM is to work within these natural systems to design for sustainability.

Carbon: Carbon is a basic building block of life, so it needs to be reflected within an MFA framework (rather than wood *per se*). As mentioned above, the efficiency of carbon fixing in whole trees and forests is estimated by scaling-up the action of individual leaves.

We are using GIS land-cover mapping of the ACR (25 land-cover classes commissioned for another project several years ago) to provide a basis for calculating stocks based on carrying capacity for different forest types. Wood flows available from a number of sources (NSW, ACT and CSIRO Forestry) have all published estimates of stocks and flows. The reconciliation of the different data sources in this area is necessary as well.

Diagram 5 (Appendix, p. 62) provides a conceptual map of carbon flows. The relationship between the stocks and flows in this map are well accepted and can be applied at local, regional, national and even a global basis. Sustainability requires 'carbon in' to balance with 'carbon out'. However, the precise mechanisms driving the flows are not well understood and possibly vary from place to place. Measurement of carbon flows and sinks is particularly controversial at present because methods of measuring carbon levels in soils are not well established. The notion of carbon 'sinks' is based on a linear input (resource)/output (waste) view of human activity. Neither nature nor the MFA approach has any use for concepts such as 'waste' or 'sinks'.

Future work examine the specialist literature in plant physiology, the earth and atmospheric sciences and biology generally, to provide improved measures of carbon stocks and flows.

Phosphorus. Like carbon, phosphorus is a crucial element in sustaining life. We have chosen phosphorus as our representative nutrient for a number of reasons:

- It is the central element involved in energy transfer and enzyme communication in all life forms.
- Australian soils are generally very short of it.
- Australia exports over 60 000 tonnes of soluble phosphorus per year which ends up in the waste systems of our customer countries and is not returned.
- The fertiliser costs at the farm gate (of which soluble phosphorus is a major component) are about $2.5 billion per year.
- Phosphorus — principally from erosion — is a major cause of the eutrophication of waterways (Starr *et al.* 1999).
- Like fossil fuels, guano and other readily accessible sources of soluble phosphorus are running out.
- While some plants have the capacity to break down insoluble phosphate rock (through the release of acetic acid from the roots) to make it available as a plant nutrient, the process is extremely slow. Such plants can be (and are being) used in rotation as a green manure with edible crops (as is being experimented with in some arid parts of Africa).
- There is a long-term possibility of developing some food crops to use rock phosphate.
- Substitution is impossible, and manufacture from insoluble sources or extraction from seawater is prohibitively energy intensive.

Diagram 6 (Appendix, p. 64) provides a conceptual map of the phosphorus cycle.

Table 7 (A.D. Brown, in press) gives phosphorus data for Australia. The seriousness of the loss of phosphorus from Australian soils was first pointed out in the early 1980s (Lipsett and Dann 1983).

Table 7. The fate of phosphorus contained in one year's Australian primary produce.

Item or process	P content (tonnes)	Proportion (%)
All produce	107 488	100
Distribution of produce		
Exports	62 325	58
Sugarcane	9 698	9
Food waste	8 670	8
Sewage	20 838	19
Assimilation	86	0.1
Total accounted for	101 617	95

The total P content of all primary produce and of exported foodstuffs has been estimated by Duncan Brown (A.D. Brown, in preparation, Table A14) largely from material published by the Australian Bureau of Statistics (ABS). Sugarcane is listed here, but not in Brown's Table A14 because the cane is removed for milling and the extracted residue is rarely, if ever, returned to the soil. The amount of sugarcane was derived from ABS 1991data. The amount of P in sewage was calculated on the assumption of a per capita discharge of 300 L/day containing 11 mg P/L. Food waste was calculated on the basis of 100 kg/head/year (van den Broek and Hatton, NSW Environment Protection Authority, pers. comm. 1992) and a guessed P content 0.5%. 'Assimilation' refers to the assimilation of P into a growing population. It was calculated from the difference between deaths and live births for calendar year 1990, an assumption of average body mass 60 kg and a P content of 1% in the human body.

4.3 Soil structure

A concept that brings together the three indicators listed above and addresses the most central problems in regional Australia is soil structure. Soil structure is the primary determinant of plant health. Although farmers have always known the importance of soil, it is only recently that the biological sciences are beginning to understand the rich complexities of subterranean ecosystems and their importance for what goes on above ground (see, for example, Reganold *et al.* (1987)).

Soil structure can be thought of as the sponginess or porosity of the soil. Soil consists of a porous mass of organic matter, rock and other particles that provides the habitat for vast numbers of organisms: bacteria, protozoans, and larger invertebrates such as worms. Plant roots open up micro pores throughout, which permit movement of air and water. We estimate that, before European farming, the soil layer in Australia in our prime agricultural areas may have been up to 70 cm deep. Now it is down to 20 cm and declining rapidly.

As a rule of thumb, the surface area of a typical plant below ground exceeds the surface area of the leaf canopy above ground. It is the surface area that provides the best measure of the capacity to take up water, carbon, nutrients and energy in photosynthesis. The total biomass of living materials (ie. the existing stock of all living organisms) is greater under the ground than above it.

Diagram 7 sets out the conceptual (not causal) relationships between soil structure and the various problem areas recognised in Australia. If the soil is spongy, it will hold more water (thus reducing run-off, erosion and leakage into groundwater) for a longer time, thus reducing the need for irrigation. The organic matter in the soil that is partly responsible for this water-holding capacity will improve soil ecosystem functioning and stimulate plant growth. Natural regrowth of deep-rooted vegetation reduces the cost of planting. Decreased run-off will in turn reduce erosion and the scouring of river courses. Less erosion means less weeds and so on.

Improving soil structure: Improved soil structure can be achieved in two ways:

1. by leaving it *in situ* and, where possible, returning as much organic matter to the soils in the form of manure, compost, humus and natural fertilisers (eg. blood and bone); and
2. by reconstituting soil structure through the addition of suitable plants and micro-organisms (soil building). For example, where soil micro-organisms are out of balance, the balance can be reinstated through organic means rather than by adding chemical nutrients or pesticides. Organic balancing is the process where small samples of soils deficient in organic activity are brought back into balance under controlled conditions and then used to seed the deficient soil.

The first of these (returning nutrients or organic matter to the soil), is in common practice in Europe and in intensive horticulture in Australia. Unfortunately, grazing or broadacre farming in this country is unsustainable ‘nutrient mining’. Such has been the loss of organic matter from Australian soils since European farming methods began, that returning all organic matter from urban and animal sources will not be enough. Soils in Australia cannot be reconstituted through the first means alone. That is, even if Australia achieves zero organic matter going to landfill, lost to sea as sewage, burnt to ‘clean up the paddock’, or used for generating energy, only a small proportion of our degraded lands would be restored, especially in the intensive land-use zone (39% of the Australian continent). Land degradation is occurring at so great a rate that agriculture cannot become sustainable without soil-building strategies.

Diagram 8 (Appendix, p. 66) shows the relationships between soil structure and key environmental problems affecting rural Australia.

4.4 Applications

Integrating GIS and MFA

We have begun experimenting with different types of mapping presentation (a selection of which is included in this report) to ascertain which approach works best in a community context. Aerial data collection and mapping is directly relevant to MFA in two ways:

1. It identifies regional **stocks** and provides a basis for some flows. Stock data include land use (agriculture, urban, etc.) and land cover (grassland, forest etc.). These data can be used to estimate biomass.
2. GIS maps enable **flows** data to be superimposed on them to identify bioregional boundaries and resolve system boundary issues.

The variety of GIS data available is also important, such as electromagnetic radiation (light, infrared) and radiometrics (gamma radiation). Ground-truthing of these data is showing unexpected patterns. For example, radiometric data on salinity are revealing the existence of salt in areas which CSIRO and LWA modelling predict should *not* be at risk of salinisation.

In urban areas, heat loss from the built environment can be mapped at the level of individual houses and even individual rooms (we are exploring the use of this capability to reduce energy losses).

A series of workshops to address these issues is being planned through the Nature and Society Forum (NSF). This group has previously undertaken integrative work on infectious diseases, food and energy. Dr Moss Cass (Australia’s first Environment Minister) is convening a new series of workshops on salinity and is offering invitations to key CSIRO, university, business and academic personnel to explore some of these issues.

Rural revitalisation

Independent oil analysts now believe that oil prices will rise dramatically when total world reserves are half depleted (Hatfield 1997). The oil industry, worldwide, may be able to recover another 1000 billion barrels of conventional oil — little more than the 800 billion barrels that have already been extracted. However, production will peak around 2010, after 900 billion barrels are consumed (Campbell and Laherrere 1998). Australia imports over 60% of its oil, and relies heavily on imported oil for diesel fuel used in farming. Therefore, Australia’s key industries are vulnerable to increasing international oil prices, or more so due to a lack of availability. Renewable energy consumption has increased by 50%, but this is far less than growth in fossil-fuel use.

The fossil-fuel-based economy is a linear (extraction–use–waste) system. It also transfers social and environmental costs in one direction and wealth in the other. ESD will therefore require a shift away from the ‘old economy’ industries characterised by fossil-fuel dependency in transport, energy production, manufacturing and materials to solar energy and plant-based materials.

According to David Morris, the US Congress is appropriating hundreds of millions of dollars to accelerate the move to a ‘bio-based economy’. Not only will this increase national security [the US imports 53% of its oil] it has the potential to improve the rural economy. Therefore, the US is more than doubling the tonnage of plant matter being used for industrial markets, which will spawn thousands of new regional bio-refineries (Morris 2002).

> With virtually no government assistance, more than 150 farmer-owned manufacturing facilities with a capitalisation of more than $3 billion have been created in the last 15 years. In Minnesota, in-state ethanol plants provide about 10% of all automobile transportation fuels. Two thirds of the 15 biorefineries are owned by some 8,500 farmers. (Morris 2002)

Plants can be used as a resource for healthy materials and biochemicals (in place of petrochemicals). Almost everything that can be made from hydrocarbons (fossil fuels) can be made from carbohydrates (25 000 products made from hydrocarbons can be made from plants (eg. bamboo, straw, non-narcotic forms of hemp). Products made from plant matter can also be made recyclable and avoid many of the toxins dispersed by hydrocarbons throughout the product life cycle.

Due to the weight of bulk agricultural materials, primary processing of plant-based products will occur in rural regions. In fact, farmer cooperatives for light manufacturing of bio-based building materials are rapidly emerging in the US.

One of the most immediate interventions for rural Australia suggested by MFA analysis may be green business incubators. The analyses will provide the basic information and research, as well as a sustainability audit of the ACR, to assist rural entrepreneurs in developing eco-innovations. John Schooneveldt has extensive experience in the area of stimulating business enterprise and innovation. Farmers co-operatives to establish biorefineries for ethanol, compost plants to replace chemical fertilisers, or healthy building materials are likely contenders for new rural enterprises. These potential rural industries could contribute to the resolution of several critical Australian environmental issues simultaneously:

- reduce pressure on remnant native forests
- lower construction costs
- reduce greenhouse emissions
- improve public health and occupational safety
- reduce indoor air pollution
- provide income for farmers
- diversify the rural economy
- increase national economic security through fuel independence
- contribute to biodiversity conservation, if properly managed
- address the serious salinity problem in Australia.

Differences in demographics suggest that further analysis is needed before a similar investment is made in Australia (ie. transport differences can change the economics). MFA can provide the analysis and supporting data to guide policy-makers about resource options in different regions to revitalise rural economies in Australia.

Problems with bio-fuels

In Australia, there has been little analysis of the potential diversification into petrochemical substitution products. Of the thousands of products that can be made from plant materials, the most widely discussed are bio-fuels. It is therefore important to note that ethanol fuel production is not the best use of plant materials from an ecological perspective. If spilt, for example, the effects of biomass fuels on a waterway are as harmful as petrochemical fuels.

Biomass fuels are cleaner than petrochemical ones in that they contain negligible sulfur. The carbon dioxide released into the atmosphere by burning or other form of energy extraction is roughly compensated for by regrowth. While biomass fuels are not yet competitive with other transport fuels, this is partly due to hidden subsidies enjoyed by other fuels (eg. the externalisation of environmental and public health costs). These fuels are, nonetheless, no long-term substitute for solar electric or fuel-cell powered transport. However, a major impediment to fuel cells is that production of hydrogen may be sourced from non-renewable sources. Biomass could possibly be an appropriate source of hydrogen to power fuel cells. Extensive research by the US Environmental Protection Agency and other bodies in this area may resolve such issues.

5 Summary: MFA in the framework of the four integrating themes

As a means of summarising our progress, we discuss this research in relation to the framework of Land & Water Australia's four integrating themes.

5.1 Perceptions and values

Goal: Acceptance of multiple perceptions of environmental problems, with the development of a holistic view with strategic action and the capacity to act for better natural resource management.

Output: Provide enhanced understanding, tools and methodologies for evaluating perceptions and valuing landscapes and ecosystem services.

5.1.1 Identify prevailing perceptions that are constraining the development and adoption of more sustainable systems of resource management.

Our research applying MFA to regional issues challenges a number of prevailing perceptions in NRM. A couple of these are listed here.

Retrospective tools: Policy research in the NRM fields still contains vestiges of methods, tools and strategies developed within the dominant positivist science paradigm. While the ability to predict, accommodate, monitor and control (rather than learning to work with natural processes) is an important aspect of solving many kinds of problems, it is less useful in issues of social change. A key perceptual problem addressed in this report is the tendency to apply conventional scientific methods (that were developed to explain existing conditions) to issues concerning the design of sustainable futures. Sustainable development requires forward-looking 'system design thinking', not just linear predictions or projections of past trends. Our MFA approach shifts away from retrospective, quantitative analyses towards systems redesign and is geared toward enabling the community to focus collectively on win–win options.

Ecosystem services: Cities and, more generally, all development, have been conceived as mechanisms that are independent of the bioregion (ie. the economic, social and ecological region that the urban area draws its resources from). Sustainability, in contrast, requires that all development exists in a reciprocal relationship or net resource *balance* with the hinterland. Cities do not need to be a drain on the bioregion. As physical 'plants', cities can be designed to reduce their impact on rural Australia (eg. buildings can be designed, or retrofitted, to collect and recycle all water from the site, and clean the air, or even sewage, and build better soils. The use of MFA as a broad framework, incorporating (potentially) subsidiary concepts like 'ecological footprints' and 'ecosystem services', has the potential to assist in a shift to a whole-systems understanding.

5.1.2 Explore ways to shift these perceptions on individual and community levels.

Creating a sense of care: There have been many forms of arguments as to why society should change: ranging from rational self-interest and economic ones to ethical arguments, and appealing to authority, optimism or fear. However, merely understanding human interconnectedness with nature is not enough to motivate change in most people. People need to have reason to care and must have positive and feasible alternatives. For example, few people realise that, every day, thousands of children suffer permanent retardation and disability from environment-related causes (unclean air, water and sanitation, floods, droughts) most of which can be linked conventional forms of development (see World Health Organization website). MFA can show more graphically which chemicals and quantities are building up in the environment, and how these could be improved upon by alternative development options.

Perceptions of externalities: There is still widespread acceptance of the economists' description of environmental problems as externalities (public costs of private economic activity). This concept has perceptual consequences, as it conveys the idea that the causes and consequences are external to the system. In fact, the cost of restoring Australia's land and water resources has been estimated to exceed the $37 billion annual value of the agricultural product by CSIRO, so the existing system is too costly. Yet organic agriculture is often described as requiring subsidies, while the hidden subsidies to petrochemical-based industrial agriculture are not mentioned. Similarly, in urban planning, public transport is referred to as subsidised, yet it in fact reduces the enormous hidden subsidies to cars (eg. $464 billion a year in the US). This is because the status quo is taken to be cost neutral, when in fact it is more costly than other options. When concepts are placed in economic terms, it also suggests that the problem is one for economists to solve, which is disempowering to the wider community. MFA avoids this misleading paradigm, and shows that 'externalities' are really an inherent aspect of the economic system.

5.1.3 Review existing systems for insight into the values placed on Australian ecosystems and natural resource use.

This report shows how MFA can contribute to the existing management systems and conceptual *frameworks* that are applicable to NRM (industrial ecology, urban metabolism, state of environment reporting, ESD reporting, ecological footprint analysis, eco-efficiency, design for environment principles, and so on). It also argues that our approach can integrate with, improve upon, or in some instances even supplant, traditional *assessment* tools used in NRM (such as life-cycle assessment, environmental-impact assessment, risk–benefit analysis, embodied energy analysis, genuine progress indicators and environmental quality indicators). Existing methods reflect the value placed on knowledge acquisition over methods of community design and problem solving. While each analytical method and framework has its place, they are often too complex for the rapid on-ground decision-making that occurs in planning and politics. While great (rhetorical) value is placed on transparent processes, multidisciplinary input, and participatory planning in actual application, the methods themselves tend to be complex, resource intensive and intimidating to lay people. Our version of MFA overcomes many of these failings and is compatible with the idea of designing sustainable futures.

5.1.4 Create robust and widely applicable methods to better value, account and assess the health and values of Australian ecosystems and natural resource use.

Simplifying indicators: We have reversed the standard approach of assessing anything that lends itself to quantitative measurement, and then grouping indicators into categories. Instead, our new approach to development assessment has been to determine the fundamental systems issues first. Once the framework and important things to measure are determined, we then identify simple and direct means of addressing these problems through ecological design or 'closed-loop' thinking. That is, measurements relate to factors that improve key systems issues (eg. carrying capacity, dematerialisation, genuine process) rather than impacts alone. The simplified project review process at the regional level (using only three basic indicators that also serve as design criteria) allows cumulative regional impact assessment to be conducted.

Health focus: The conventional approach of measuring symptoms within environmental media (eg. air, water) in regions is fraught with difficulties. Our approach to establishing boundaries at the regional level enables us to refocus NRM on trying to optimise the health of critical systems (rivers, forests). We do this by looking at the stocks and flows of simple elements by weight rather than whole regions. This can also help move indicators away from measuring the resilience of nature to assessing the achievement of human organisations responsible for environmental improvements.

5.2 Learning and understanding

Goal: Efficient integration and dissemination of information in an accessible and useful format that encourages learning and understanding of environmental issues and their solutions.

Output: Enhanced understanding of Australian landscapes, climate, biota and ecosystem processes, and their implications for management.

5.2.1 Identify issues where gaps in understanding are a key constraint.

*Data gaps and reconciliation***:** MFA serves as a true 'audit', because it provides a means of identifying inconsistencies and gaps in data. The validity of our new approach to systems boundaries is demonstrated by our discovery that the existing official figures on water, wood and energy resources in Australia do not add up. This has serious implications for NRM policy. In every area that we have examined using MFA (water, energy, wood, salinity) we have found huge data discrepancies.

Importance of soil structure: By looking at stocks and flows, MFA also can rectify the past tendency to undervalue the importance of soil structure and healthy, biodiverse soil organisms. Strategies that return nutrients from organic waste and animal excreta to the soil in urban and rural areas would address several of Australia's critical problems at once. We are now examining strategies that improve soil structure and which simultaneously improve a host of other issues, such as erosion, water evaporation and compaction by hooved animals. We are working with those who are leading the effort to establish systems to turn waste into soil.

5.2.2 Develop better ways of learning to fill the gaps in understanding.

Data reconciliation: As mentioned above, our new approach to dealing with the problem of regional boundaries provides a way of finding gaps and reconciling data. However, we are also addressing gaps in MFA itself by extending the application of 'urban metabolism' models that are beginning to emerge overseas and in Australia to the relationships between urban and rural areas and different regions. Further, by gearing MFA more directly towards development and design issues, we are directing research towards 'the lowest fruit' — areas where resources and energy can be saved while creating jobs and profits. This puts ESD on a positive footing and shifts the debate from 'conservation versus development' to harness market forces towards 'doing well by doing good'.

Eco-innovation: MFA is also a very useful tool for generating ideas for eco-innovation. Calculating transfers of natural and manufactured capital out of an entity in relation to existing stocks and resources flowing in, would enable environmental managers to discover where the biggest 'leaks' in the systems or build-up of substances are beginning to occur. These can become leverage points for action. For example, high levels of waste products can become the raw material for a new regional industry. MFA can assist in developing innovations where gaps in understanding have existed in the past, such as in the retrofitting of the built environment, or finding opportunities for light rural manufacturing.

5.2.3 Foster individual understanding and innovation through information transfer.

Mapping: MFA is a practical communication vehicle for citizen understanding of the interdependence of human and natural systems. MFA communicates complex regional development issues by the use of simple visual maps and diagrams of material flows, that can capture the imagination of the lay public. Metabolic maps (whether presented in the form of participatory GIS or transparencies) will assist primary producers, decision-makers and the community at large, in visualising the long-term implications of alternative development options, new green business and eco-innovations. In association with other researchers, we are beginning to work on integrating geographic information systems (GIS) with MFA and to apply these tools to regional development issues, such as salinity and soil quality.

Education: We have given several public presentations on that highlight some of the key systems issues facing the Australian Capital Region. We are about to convene a seminar series to share information among experts in areas relevant to new applications of MFA through the Nature and Society Forum (a community-based group committed to promotion of the health and wellbeing of people and the environment) and the University of Canberra. We are also establishing a set of postgraduate courses at the University of Canberra which will promote more research and capacity building in systems-design approaches to NRM (the course is described in Box 4).

5.2.4 Foster collective understanding and innovation through relationship-building

The project has sought the expertise and assistance of a cross-section of the community through the creation of a board of advisors. The research team itself is transdisciplinary, and has drawn on the expertise from science, policy, medicine, government, industry, farming, education and community sectors. Moreover, our research has attracted significant attention from people in several areas and we are working with a rural community (Bombay Landcare Group) to establish an on-ground pilot project. This community group is interested in using MFA to find regional development opportunities that are consistent with ecological sustainability, and also improve regional agricultural practices generally. We are developing a strategy for wider dissemination to regional communities for the next stage of the project.

5.3 Living in and managing

Goal: Ecologically and socially sustainable practices for living in and managing human–environment interactions in Australia.

Output: Understanding, tools and methodologies for more sustainable management of natural resources.

5.3.1 The impact of human activities on the environment at a range of scales. For practical purposes these can be summarised as: farm scale, catchment or regional scale, national scale.

Project specific: A low-cost, quick means of determining the impacts of development is necessary to support community-based bioregional governance. Our project has developed the basis for a practical set of criteria/indicators to serve as both design guidelines and assessment criteria for regional development proposals. This also provides a simplified form of integrated assessment so that communities will be able to test and verify development proponents' assertions and planners' assessments.

Regional planning: MFA provides a quantitative and objective basis for futures planning using scenario and least-cost planning for assessing regional resource development options. MFA can be used to establish a concrete basis for waste reduction and eco-efficiency strategies at the regional level by determining areas of waste or inefficiency and their social, institutional and industrial sources. Generally, on-ground solutions need to be found at the regional level where resource options and impacts can be determined. Using information from regional MFA analyses, each region could determine additional criteria/ indicators to address problems that are unique to their area.

National policy development: MFA provides a strategic process for finding new markets, products and services that Australia can sustainably serve. MFA would allow a shift from finding resources to meet the needs of the existing industrial (fossil-fuel based) development system, to finding environmentally benign resource substitution and import replacement products and processes. Examples of the national policies assisted by MFA would be the promotion of light, regional manufacturing of bio-based building products, research into the means of improving the structure of soil, and nutrient replacement strategies in agriculture.

5.3.2 The demands placed on the environment by consumption patterns and prevailing technologies where this falls within Land & Water Australia's mandate.

Demand reduction: MFA is a conceptual framework that can help shift thinking away from individual consumer behaviour to systems redesign. Much of consumer demand is supply driven, so eco-efficiency is not a substitute for redesign of basic systems of production, including agriculture. The traditional focus on what individuals can do to cut household waste — though important and having upstream effects — is not as well targeted as eco-innovation in resource extraction and production processes, in the design of the built environment and transport systems, and in bioregional level planning. For example, Australian householders dispose of 620 kg per person per year, but Australia requires a total material flow of about 180 tonnes per person per year to support the population's lifestyle (Poldy and Foran 1999) due to the materials and processes used in producing goods. That is, consumers are trapped in large systems that behaviour alone cannot change. MFA allows us to identify processes or activities in the human-made environment — infrastructure, cities, buildings, landscapes and products — that are dysfunctional or inefficient, to target the greatest areas of waste and pollution.

Rebound effect: The 'rebound effect' occurs when a portion of the income saved through more efficient production is spent on increased material consumption (Harrison 2002). Current trends suggest that the rebound effect will continue to reduce net-efficiency gains. This means that substantive life-quality improvements which meet basic social and emotional needs must be designed in such a way that they reduce material consumption while improving quality of life. Work towards the development of a genuine progress indicator (GPI) is beginning to account for this personal, subjective dimension of needs and preferences (Eckersley 2002). However, these indicators do not address the role of systemic problems (eg. poor transport infrastructure, pollution, congestion) in reducing life quality. Neither do they account for the potential of the built environment and design to improve life quality.

5.4 Organisations and governance

Goal: Adaptive and aware governance and organisations that lead and respond to diverse needs and move towards improved environmental outcomes.

Output: Knowledge underpinning effective institutions that encourage sustainable natural resource management.

5.4.1 Evaluate institutional arrangements and make inadequacies and their perverse outcomes transparent.

Intellectual frameworks: While the concept of 'systems thinking' is prevalent in the language of NRM, the practice does not match the rhetoric. As mentioned in earlier sections, the intellectual frameworks of the policy fields most directly concerned with decisions relating to environmental quality often remain linear and reductionist, more process-focused than outcome-oriented, and concerned with increasing descriptive knowledge rather than with social construction and design. Concepts such as 'sinks', 'eco-efficiency', 'cleaner production' and 'recycling' are essentially end-of-pipe solutions and fail to address the fundamental underlying systems problems.

Institutional arrangements: Institutional arrangements need to reflect systems thinking. Transdisciplinary approaches that bridge the arts, sciences and humanities are becoming increasingly valued. Research has shown that some CRCs are encouraging specialists from different sciences (and with different views of science) to work together. But despite some tinkering with institutional and professional hegemonies, there is still a long way to go. MFA can help to improve interaction and communication between science, policy and community on environment and development issues, by creating a whole-system perspective and a language that is acceptable to scientists and accessible to the wider community. Because our new method is simple and robust, it is capable of being applied by the community to verify the claims of developers and decisions of planners.

5.4.2 Assist institutions to lead and respond to diverse and changing issues in natural resource management.

Triple bottom line: By focusing on mechanistic policy-making strategies (levers and pulleys), NRM has tended to overlook direct preventative design solutions, and adopt costly remedial strategies (treating symptoms). Being able to map a region's metabolism is essential to achieving regional governance and sustainable economies. MFA can integrate social, economic and environmental dimensions of NRM. This 'triple bottom line' is an essential basis for design — creating symbiotic relationships among larger systems: urban form and infrastructure, construction and agriculture, services and distribution systems.

5.4.3 Contribute to policy debates on appropriate institutional arrangements at a range of scales.

Government policy: Australian governments have recognised that NRM at the bioregional level is an essential step towards sustainability and rural and regional revitalisation [eg. *Managing natural resources in rural Australia for a sustainable future* (AFFA 1999); *A revolution in land use: emerging land use systems for managing dryland salinity* (CSIRO 2000); and *Our vital resources: national action plan for salinity and water quality* (www.napswq.gov.au/publications/vital_resources.html) (with joint CW and State funding over 7 years of $1.4 billion)]. A key government strategy is to devolve decision-making powers to regions, as resource-management issues can best be dealt with at a regional level and scale. However, improved decision-making processes and techniques for NRM are needed. Our project shows how MFA can provide institutional and technical support for both forward planning and project assessment.

Issues: Community debate over new institutional arrangements requires confidence in the future and knowledge of the many issues and stakeholder positions. A simplified model and practical decision-support tool will, in itself, help to empower regional communities. Our improved method for mapping regional metabolic processes will also provide communities with the information and communication framework necessary to: (1) plan for sustainability (ie. 'design the future') at all institutional scales; (2) raise the level of debate concerning the growing social concern in Australia over the linear flow of materials and wealth from rural to urban areas; (3) inform policy regarding resource allocation between rural and urban regions in Australia. A wider range of institutional options should be explored.

Box 4. New courses at the University of Canberra linked to this research

Note: Subject descriptions and further information are available

Strategic streams for new University of Canberra postgraduate courses
Collectively, the units create a comprehensive overview of environmental-management issues, methods and solutions. Each unit centres on a different pivotal system in the broad area of ecologically sustainable development. The students create their own self-directed program and learning goals with the assistance of staff advisors, and have external mentors for their major research projects. These research projects will generally be within one of the streams (below).

Stream A. Eco-innovation
Economic competition in a global economy requires new approaches to education for innovation and commercialisation, through socially relevant, ethical research that targets important human needs. Training and support is provided in skills needed to design, incubate and commercialise the kinds of strategic concepts and eco-solutions that are now challenging traditional market forces.
Example projects: Developing and commercialising a 'green' product, service or process; establishing a detailed business plan for a green business incubation program.

Stream B. Appropriate technology
Developing countries cannot achieve the same standard of living as privileged nations *unless* global resource consumption is dramatically reduced in all nations through appropriate design and technology. Principles, processes and methods for designing integrated systems and eco-solutions are presented that address needs through appropriate design, transfer and adoption of 'living technologies' (such as buildings that produce energy and purify air and water).
Example projects: Assisting a village or non-government organisation (NGO) in a developing nation to find a cost-neutral or profitable solution to waste or water treatment; designing and implementing emergency housing or micropower generation systems.

Stream C. Bioregional development
Problems of salinisation, water depletion, erosion, reduced biodiversity and rural economic decline must be addressed through whole systems solutions at a regional scale. New techniques are provided for mapping and redesigning systems to foster regional revitalisation (such as ecoforestry, bio-based building materials, energy production or desalinisation) that add economic value — while rehabilitating damaged ecosystems, preserving natural and cultural heritage, and restoring biodiversity.
Example projects: Instituting an adult environmental education program (eg. learning circle kit) about opportunities for regional revitalisation; developing a proposal for improving agroforestry methods.

Stream D. Sustainable urban form
The concepts and assumptions which shape urban development and create negative consequences (eg. social alienation or crime), and are a drain on surrounding regional/rural populations and ecosystems. A rigorous framework is provided in which to develop alternative policy options and innovative approaches to the redesign of urban and suburban settlements.
Example projects: Producing a documentary film on the relationships between resource consumption and urban design; exploring practical means to increase urban biodiversity and ecosystem services.

Stream E. Assessing design and development
New sustainability indicators, analytical tools and performance measures are needed to perform SoE and ESD reporting which are increasingly required of government agencies and public corporations. A critical examination is provided of techniques for evaluating the costs, benefits and risks of existing or proposed designs of manufacturing, agricultural and resource extraction systems, land-use patterns, buildings, products, and other forms of development (eg. sustainability/environmental indicators, environmental management and reporting systems, impact assessments, building rating systems, ecological footprint and environmental space analysis, risk analysis).
Example projects: Working with local government to develop improved project review processes and assessment tools; designing a prototypical ecological home or building component.

Stream F. Eco-governance and social change
Emerging values, a new ethic, and a recognition of the increasingly global nature of environmental issues (urbanisation, economic globalisation) are challenging the assumptions underlying resource management and environmental planning frameworks, and its interface with the economy. The course translates the extensive but highly theoretical work in eco-governance to on-ground applications in a variety of contexts.
Example projects: Serving as 'consultants' within public institutions or NGOs to identify systemic issues and develop specific means to resolve them; improving a local government design approval process.

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Appendix

Introduction

The accompanying diagrams and explanatory notes are illustrative of the types of mappings that result from the application of MFA. Only the first diagram (in relation to water in the ACT) is approaching a comprehensive mapping of available stocks and flows data. The remaining diagrams require further work in defining geographic boundaries and inserting relevant stock and flows data (where data exist) or identifying gaps where they do not.

We are experimenting with various styles and modes of presentation. These will be further evaluated, validated and improved during the consultation phases of future work.

The term ‘diagram’ as used here refers to a representational device that illustrates underlying processes and/or relationships that cannot be expressed in precise terms, as would be the case in modelling approaches. Models typically involve properties that can be subjected to mathematical analysis, particularly in a reductionist framework. In the MFA context, we are seeking to communicate whole-system concepts involving more complex and less readily measurable relationships.

The processes and relationships presented in these diagrams are basic physical stocks and flows of materials that are important to the human condition. Where possible we measure them in terms of weight, but for the present, water is measured in gigalitres and energy in joules.

As pointed out in the body of the report, there are vast amounts of data available, but they need to be reworked into this new framework. When complete, the diagrams are expected to provide some sense of the relative scales of the flows as denoted by the width of arrows, and the size of stock as denoted by the area of the relevant box.

In addition to stocks and flows, related systems concepts such as feedback loops, control points, bottlenecks, capacity imbalances, buffers and leverage points will be introduced as future work proceeds.

Diagram 1 — Water

General

The figures on water have been specifically collected for this project. This diagram is indicative of the potential of the MFA technique. We expected water data to be compatible across sources, but found that variations in sampling methods and frequencies result in huge inconsistencies. If confirmed, these results will have important implications for planners and decision-makers. More work is needed to validate these results before policy-makers use them.

Ideally, all water-flow figures need to depict their daily, seasonal and/or decadal variation. This is not practical, however, so *average* figures have been used, expressed as gigalitres per year. It should be noted that these averages disguise exceedingly large flow variations. For example, the water database suggests that the minimum daily flow in the Murrumbidgee at Hall is 2.4% of the average, while the maximum is 8898%. As with all rivers, the median flow is below half, at 41%. All tributaries of the Murrumbidgee in this area have had zero flow at some time during the last decade.

As the ACT is wholly contained within the upper Murrumbidgee catchment (Map 1), its flows need to be placed within the context of upper Murrumbidgee flows. For now, this mapping is based on flow volumes given in the "Water Resources Management Plan" ("the Plan") prepared by Environment ACT (1999). In a couple of places, estimates have been added from the "Sub-catchment Flow: Proportion of Inflow to Burrinjuck Reservoir 1960–76", prepared by the Department of Construction and Binnie International (1978). Both documents cite exactly the same flow volumes into Burrinjuck Dam (1383 GL), so there is a high possibility that these calculations have the same source.

Rain

The Plan cites an average annual rainfall of 724 mm. Various other documents (eg. the Australian National Water Resources Audit[1]) refer to a figure closer to 645 mm. The Plan's figure could be inflated by the number of higher altitude, non-ACT areas covered on p. 53, as the higher altitudes have a rainfall figure of 800–1000 mm, much higher than Canberra Airport's 600 mm. However, we have used the Plan's figures so as to be consistent with the averaged evapotranspiration figure (see below).

Gross rainfall input then is:

$$724 \text{ mm} \times 2290 \text{ km}^2 = 1658 \text{ GL}.$$

Other sources say that the ACT is bigger at 2499 km^2. While it would be useful to be able to agree on the size of the ACT, in fact the figure, when multiplied by the claimed lower rainfall, gives a similar overall input of 645 mm × 2499 km^2 = 1644 GL).

Under the seat-of-government arrangements with NSW (discussed further below), the ACT has a direct interest in those NSW catchments that have some of their area within the ACT. This larger area extends to 3715 km^2.

However, water enters the ACT from rain falling on a much larger area that includes the upstream tributaries of the Murrumbidgee and the catchments of streams adjacent to the ACT, but excludes rain falling on downstream tributaries (the Yass and Goodradigbee rivers as well as the Murrumbidgee below the ACT). The total upper Murrumbidgee catchment has an area of 13,000 km^2 (see Map 1), but we have found no published figures covering this area so, at this stage, we cannot gauge the total flow of water through the region. For the present purposes, therefore, Diagram 1 takes average rainfall falling solely within the ACT borders and adds the average sum of water transported across the borders to calculate a net total.

Evapotranspiration

Water lost through evapotranspiration is estimated as 547 mm per year. Applying this rate to the ACT area, gives a loss of 1252 GL for a balance of 405 GL. The Plan reduces this figure by an estimated 73.1 GL 'lost' to groundwater. This value appears to have been arrived at by multiplying the 'ACT recharge' figure of 20.1 mm with the 'ACT & NSW area' figure of 3715 km to give a value of 74.7 GL. This needs to be confirmed.

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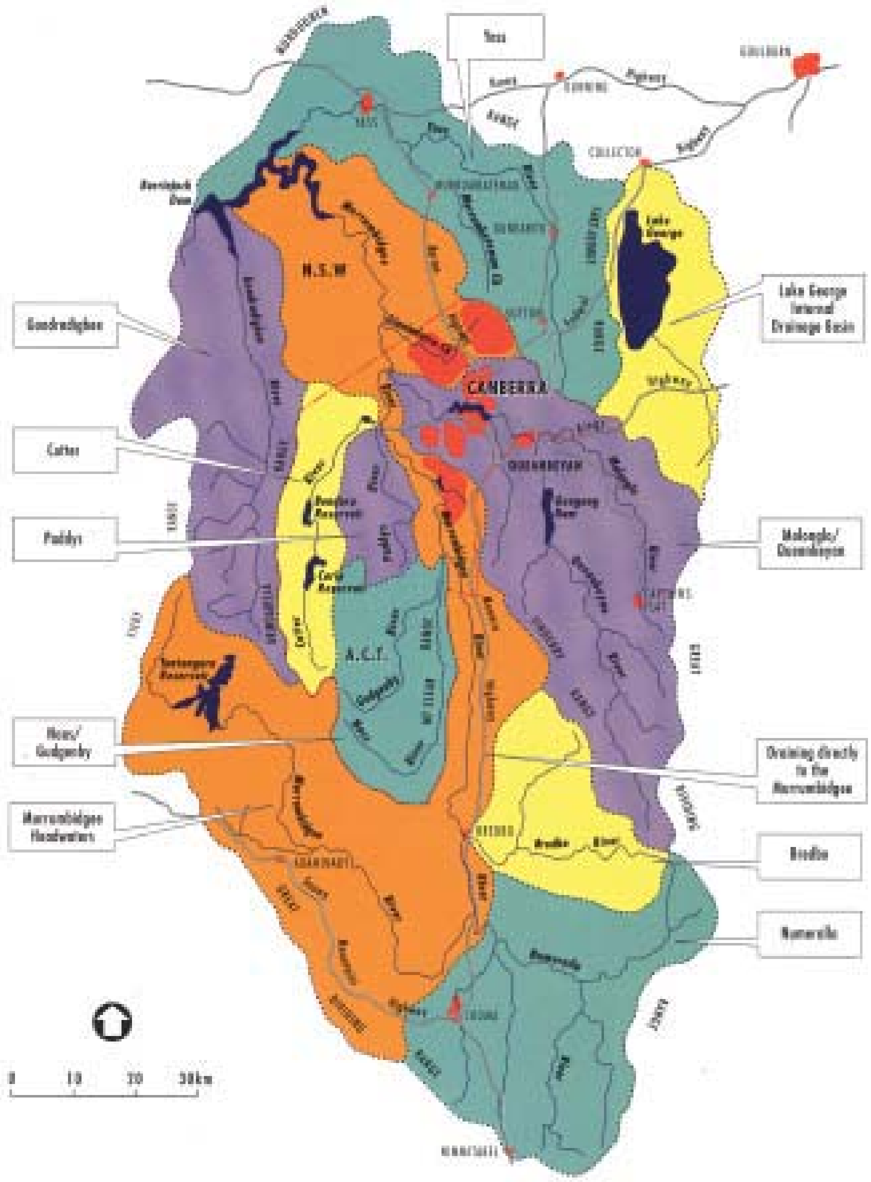
1 Online at: <http://audit.ea.gov.au/ANRA/water/docs/state_overview/ACT_ovpage.html>.



Map 1. Upper Murrumbidgee catchments (source: Upper Murrumbidgee Catchment Committee)

Despite uncertainties, this gross balance suggests that the net volume of water entering the ACT as rain and flowing into the Murrumbidgee from ACT-fed streams is around 334 GL. The balance of the ACT flows should then be from water entering by border-crossing rivers and by human intervention.

River flow

Diagram 1 and Table A1 set out the river flows discussed in this section.

Most of the figures in the Plan and other documents refer to "water controlled by the ACT" or "water in the ACT management area". Therefore it is not easy to distinguish actual flow by volume. At one point we took data from the Environment ACT water quality database and averaged this out, but the results were so hugely at odds with the published sets as to be meaningless. For example, the 20-year average annual flow of the Molonglo at the ACT border, from the database, is 118.6 GL in contrast with the Plan's figure of 48.1 GL. Furthermore, the flow of the Molonglo at Coppins Crossing is 139 GL, just 21 GL more than at the border. This cannot be, as the Queanbeyan alone adds 51 GL to this system. In total, the database suggested inflow from the Murrumbidgee of 325.5 GL at the ACT border, with an outflow of 777.7 GL downstream at Hall, for a total gain of 452.2 GL. *Although the total 'ACT contribution' seems a reasonable approximation, the other gross figures disagree with those published by several hundred gigalitres.*

Murrumbidgee

The base flow in the Murrumbidgee upstream from Michelago is missing from all figures discussing the flow of waters through the ACT, presumably because the ACT has no rights to this water. From the Department of Construction document referred to earlier, the flow at the ACT/NSW border would seem to be 428.7 GL, none of which is controlled by the ACT, and virtually none of which originates in the ACT.

Murrumbidgee tributaries

The Plan refers to tributaries of the Murrumbidgee originating in NSW but having some part of their catchment in the ACT. The total flow from these tributaries is an additional 112.5 GL. Of these tributaries, the ACT claims rights to a percentage of water equal to the percentage area of those tributaries within the ACT. Thus, flows in the Tharwa and Kambah catchments are claimed at 100%, Uriarra 65%, Guises 44%, Woodstock 25% and Michelago 4%. In total, the ACT claims 29.4 GL which actually originates in the ACT. Of the balance of the total flow (112.5 GL), 83.1 GL flows through the ACT but is not controlled by the ACT.

Molonglo

Both the Plan and the Department of Construction document would suggest that the Molonglo flows at 48.1 GL per year. The ACT claims the entire flow of the Molonglo, at least up to the old dam at Captains Flat. This 48.1 GL appears as “ACT controlled flow”; all of which does indeed flow through the ACT, but none of which actually originates in the ACT.

Queanbeyan

For the Queanbeyan catchments, the ACT has rights to the water within and below Googong Dam, and its immediate foreshores, but not control over the tributaries feeding the dam (ie. Tinderry, Burra and the Googong catchment other than the foreshores). Googong Dam is obliged to release waters equal to 80% of the inflow. Here again the figures are inconsistent. On page 12 of the Plan, the mean annual inflow to Googong is given as 114 GL, and the Department of Construction suggests 110 GL. However, the sum of the flows of Googong Dam’s tributaries (Tinderry 61.6, Googong 5.6 and Burra 7) is only 74.2 GL.

Diagram 1

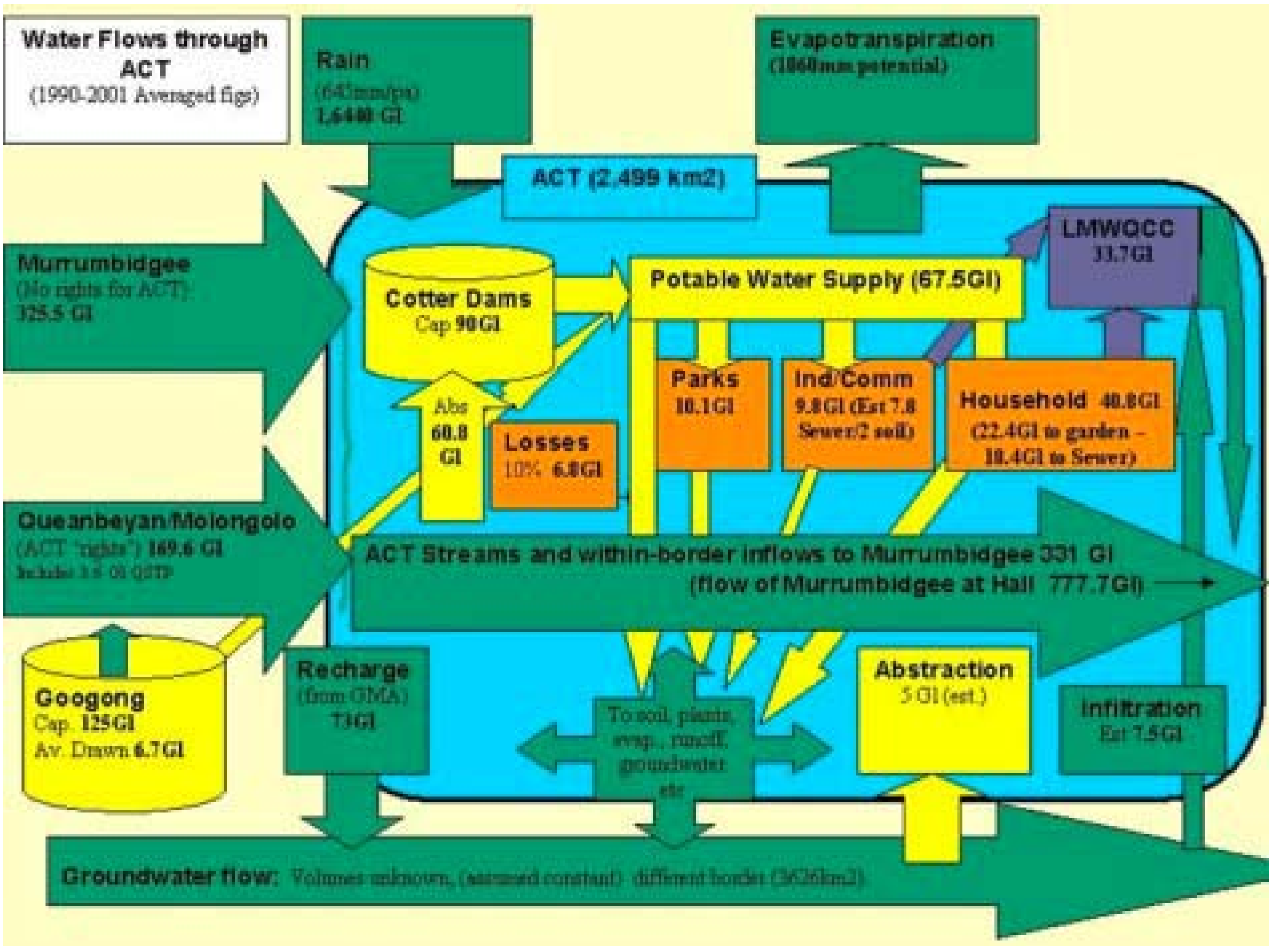


Table A1. Water flows through the Australian Capital Territory. Values are averages for the period 1990–2001.

River	Actual flow (GL/year)	Flow from NSW	Flow from ACT	"ACT controlled flow" (GL)
Murrumbidgee at Lobbs Hole	428.7	428.7	0	0
Total Murrumbidgee	428.7	428.7	0	0
Michelago	68	65.3	2.7 (4%)	2.7
Tharwa	3.7	0	3.7 (100%)	3.7
Kambah	3.1	0	3.1 (100%)	3.1
Uriarra	25.5	9.5	16 (65%)	16
Woodstock	7.3	5.5	1.8 (25%)	1.8
Guise's	4.9	2.8	2.1 (44%)	2.1
Total Murrumbidgee tributaries	112.5	83.1	29.4	29.4
Naas	42.3	0	42.3 (100%)	42.3
Gudgenby	50.4	0	50.4	50.4
Tennent	8.4	0	8.4	8.4
Corin	63.7	0	63.7	63.7
Bendora	44.9	0	44.9	44.9
Lower Cotter	46.4	0	46.4	46.4
Paddys	42.2	0	42.2	42.2
Total wholly ACT streams	298.3	0	298.3	298.3
Lower Queanbeyan: actual flow at Oaks Estate 51 GL	6.9	6.9	0	6.9
Tinderry, Burra and Googong 74.2 inflow, 44.1 released, balance to potable water	44.1	44.1	0	0
Total Queanbeyan	51	51	0	6.9
Upper Molonglo	48.1	48.1	0	48.1
Total Upper Molonglo	48.1	48.1	0	48.1
Kowen	7.5	2.1	5.4 (72%)	7.5
Fyshwick	1.7	0.5	1.2 (62%)	1.7
Jerrabomberra headwaters	6.8	6.8	0	0
Jerrabomberra	4.7	0.7	4 (86%)	4.7
Lake Burley Griffin	9.5	0	9.5 (100%)	6.8 (72%)
Sullivans	5	0	5 (100%)	5
Woolshed	6.9	4.4	2.5 (36%)	6.9
Coppins	5.9	0	5.9 (100%)	5.9
Woden	7.2	0	7.2 (100%)	7.2
Weston	4.2	0	4.2 (100)	4.2
Tuggeranong Creek	11.2	1.9	9.3 (83%)	11.2
Gungahlin	4.7	0	4.7 (100%)	4.7
Ginninderra Creek	4.5	0.6	3.9 (88%)	4.5
Parkwood	12.5	7.2	5.3 (42%)	12.5
Total 'all other streams'	92.3	24.2	68.1	82.2
Totals	1030.9	635.1	395.8	465.5
Potable water abstracted	–67.5	Av. –6.7	Av. –60.8	n/a
Water returned via LMWQCC[a]	33	0	33	n/a
Murrumbidgee at Hall	995.5	n/a	428.8	n/a

[a] Lower Molonglo Water Quality Control Centre

The flow at Oaks Estate (from the database itself) is 51 GL, of which 6.9 GL enters from the lower Queanbeyan River, below the dam wall. Given that it is frequently claimed that in a 'typical' year the Googong Dam supplies only 10% of Canberra's 67.5 GL potable water demand (eg. "Water Supply Strategy", p.37), it is unclear where the balance is going. *For the lower inflow figure, some 14 GL need to be accounted for. For the higher figure around 64 GL is 'missing'.*

Diagram 1 assumes that the inflow to the Googong Dam is 74.2 GL using the Water Quality Database averages. We take the figure of 51 GL for Oaks Estate. This suggests that the dam releases 44.1 GL to flow downstream to Queanbeyan at Oaks Estate, and is joined by 6.9 GL of lower Queanbeyan inflow including stormwater and treated sewerage from the town of Queanbeyan itself. For now, it is assumed that the balance of the inflow figure, 30 GL, is diverted to Canberra potable water, with the 'typical' year's 6.7 GL being brought up to a much higher average during 'drought years'. More accurate information will, we hope, paint the real picture.

In summary, of the 81 GL flowing into the ACT from the Queanbeyan River, 51 GL is in the form of river inflow at the ACT border, of which the ACT claims only 6.9 GL. The balance of 30 GL is problematic. In a 'typical year' only 6.7 GL is diverted into the ACT via ACTEW water pipes. This joins with water abstracted from the Cotter system, which, for a 'typical year', has a total abstraction of 67.5 GL. Of this, 55% is lost one way or another (largely to irrigation) and 33 GL is returned via the Lower Molonglo Water Quality Control Centre (LMWQCC). The situation is very unclear. When Googong is full, as it is most of the time, one would expect the input to equal the output, namely 81 GL. While the dam is filling, after being drawn down, the flow below the dam wall is presumably close to 0 while the dam fills. If the net flow is 51 GL, what then is the longer term average of Canberra's potable water demand?

We cannot show Queanbeyan diverting 30 GL via ACTEW pipes without throwing out the average domestic consumption figures, so for now, we treat the Queanbeyan as if it flowed at only around 50 GL. The balance of water abstracted and returned (ie. the difference between 67.5 to 33) is added to the common Murrumbidgee outflow.

Other streams with some NSW catchment

Several other streams have part of their catchments outside the ACT. As far as we can tell, the only one specifically excluded from the ACT flow figures is the 6.8 GL headwaters of the Jerrabomberra. All others, including Parkwood, which is largely in NSW, seem to be wholly included in the ACT figures.

Together these streams deliver 111.3 GL, all of which is claimed by the ACT, though only 68.1 GL actually originates in the ACT.

Streams wholly within the ACT

The Gudgenby and tributaries, the Naas, the Cotter and tributaries, and Paddys River are wholly within the ACT. Their total flow is 256 GL, all of which is claimed by the ACT. Of course, a substantial part of the Cotter is diverted internally via Canberra's water supply system.

Conclusions

The above figures suggest the following totals:

- The average annual total flow of water through the ACT is 1030.9 GL. It is made up of 395.8 GL generated from water falling on the ACT area plus 635.1 GL of total NSW-originating streamflow. On average, a total of 67.5 GL of this water is abstracted for urban consumption in Canberra and Queanbeyan. Of this, some 33 GL is returned as treated sewerage, for a net loss of 34.5 GL. Thus, total stream flow at Hall is 995.5 GL.
- The amount of water claimed as controlled by the ACT is less than the amount actually flowing through the ACT, but more than the amount originating solely within the ACT. This is due to legislative arrangements between the Commonwealth and NSW. Essentially, it is the waters and catchments of the Molonglo that inflate the ACT's figure. Although the ACT draws water from the Queanbeyan and "has an interest in" its catchments, it does not have control over those catchments above the dam wall, other than the immediate foreshores of the dam. The ACT has rights to the percentage of water entering the Murrumbidgee from tributaries that originate in NSW, based on the percentage of those tributaries' catchments actually within the ACT. It does not have rights over the waters of the Murrumbidgee flowing in the river at the ACT border. The total flow of a number of other streams that join the Murrumbidgee within the ACT has been counted as "ACT controlled" irrespective of the percentage of catchment actually within the ACT, with the sole exception of the Jerrabomberra headwaters. Finally, the ACT does not control the waters of Lake Burley Griffin, nor a percentage of its catchments, even though those waters are, of course, entirely within the ACT.
- The flow of water from the Queanbeyan River that enters the ACT either as streamflow or as additional drinking water supply ought to equal the volume flowing into the dam, when averaged over a long period (less evapotranspiration). This does not seem to be the case.
- Rainfall data less evapotranspiration suggest a net inflow of 406 GL. The total streamflow data suggest

surface water flows of 395.8 GL. This cannot be the case if the estimated 73.1 GL to groundwater recharge is accurate. Groundwater movements into rivers (including via deliberate abstraction), irrigation water inflow into rivers, above average stormwater run-off from urban surfaces, and greater than quoted average demand on Googong Dam, could perhaps begin to account for the difference. For example, the "Environment Flow Guidelines" (p. 9) suggests that there is between 20 and 30 GL/year run-off from urban surfaces. It is not clear how much of this has already been accounted for in the above figures — perhaps, for example, as inflow from Sullivans Creek.

- Inflow at Burrinjuck Dam is *always* given as 1383 GL of which "426 GL comprises water controlled by the ACT". The difference between the 465 GL run-off and the 426 GL arriving at Burrinjuck would seem to be 55% of the 67.5 GL abstracted and used for irrigation (plus or minus some irrigation run-off, and groundwater inflow less further evaporation). These figures all roughly accord with the Department of Construction's estimates that the ACT contributes 35% of Burrinjuck inflow (still shown in 1978 as *exactly* 1383GL) or 484 GL (measured at Yass).

Potable water supply

Some 67.5 GL is typically abstracted for potable water although, as noted earlier, it still needs to be determined if this is a long-term average covering prolonged dry periods.

The ACT future water supply strategy (ACT Electricity and Water 1994, p. 111) suggests that 10%, 6.57 GL, is lost in supply, although it is unknown how much, if any, is re-gauged along the way.

Of the volumes delivered, Department of Primary Industries and Energy figures (Smith 1998, p. 117) suggest that the domestic sector accounts for 67%, industry 3%, parks and (public) gardens 17%, and commercial 13%. Assuming the total supply has been reduced by losses to 61 GL, households take 40.8 GL, industry and commerce 9.8 GL and parks and gardens 10.1 GL.

Of this, it is reasonable to assume that all the 'parks and gardens' water is used for irrigation of one kind or another, and becomes dispersed as soil moisture, evapotranspiration, run-off or groundwater. Household water usage has been gauged as 55% garden watering (although this figure has not been reassessed since price penalties were introduced to reduce water usage). This suggests that, of the 61 GL supplied, well over half is poured on the ground. Even this is an underestimate, as the ratio of water used internally to that used externally by industry and commerce is unknown, but it is certain that some of the industry/commerce water is used for irrigation.

Consequently, the domestic sector contributes only 18.4 GL of sewage, and the industrial/commercial sector a maximum of 9.8 GL (a figure that must be less, given landscape irrigation demand). As Lower Molonglo treats 33.7 GL a year, it would seem that at least 5.5 GL of this is infiltration. In fact, from a rough estimate of the changes in flow experienced at the plant following periods of rainfall, where daily flow rises from 100 ML/day to 150 ML/day, it could be that as much as 7 GL a year of treated flow is rainwater leaking into the system. (At $320 a megalitre to treat, this would mean $2,240,000 is being spent treating stormwater through the sewerage system.)

The volume of water abstracted from groundwater for various purposes is set at 5 GL, but this is something of a guess ("Future Strategy", p.106). Total groundwater flows are basically unknown.

It would be useful to get an estimate of total volumes in stock (including soil moisture and groundwater reserves) and average residency time. These data are not currently available.

Diagram 2 — Energy flows through the natural system

Diagram 2 illustrates the flows of energy through the living systems on which all life depends. At this stage it is a generalised conceptual diagram. At a later stage we will seek to relate these energy flows to a specific area and to quantify them. It is intended as a 'stage setter' that will assist people to understand the delivery of ecosystem services in their area.

The diagram shows the source of energy is the sun where massive nuclear reactions transform hydrogen into helium and release vast quantities of electromagnetic radiation. The effective temperature of the sun is around 5500°C. Of the radiation reaching the Earth, 8% is made up of ultraviolet light, 47% visible light and 45% infrared. In terms of energy, the solar radiation reaching the earth is about 1100 W/m^2. The bulk of the ultraviolet light is absorbed by the Earth's ozone layer. (While the ozone layer is intact, ultraviolet does not reach the surface where it can harm living organisms). Much of the infrared is absorbed by water vapour, carbon dioxide and other gases. The absorption of infrared radiation is referred to as the greenhouse effect and accounts for the

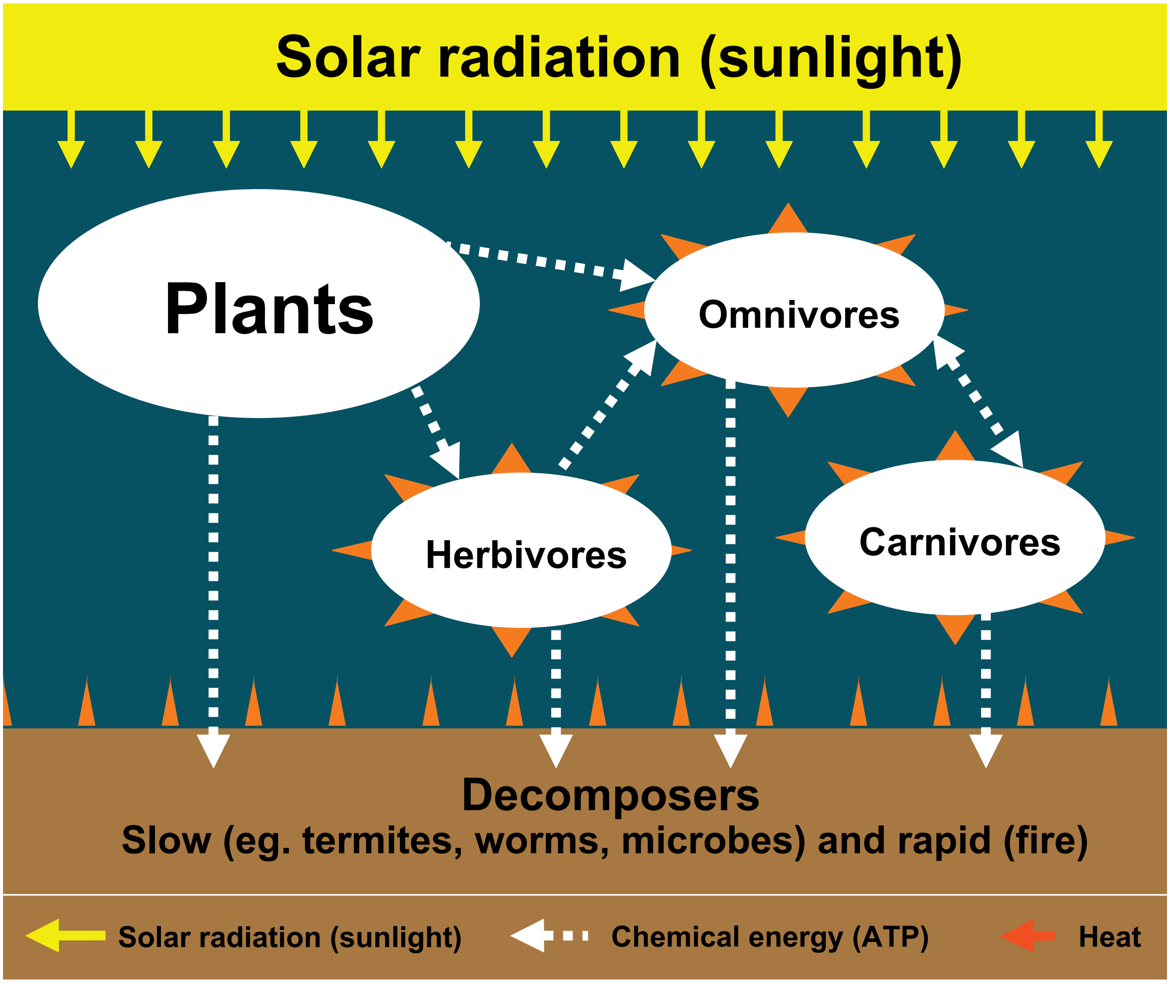


Diagram 2. Energy flows in the natural environment

Earth having its current climate patterns and, in particular, current average temperatures. If this absorption did not take place, the average temperature on the Earth's surface would be –18°C and vary enormously between day/night and winter/summer.

As its name suggests, humans and many animals use the visible spectrum for vision but, much more importantly, it is used by plants that turn it into chemical energy in the process of photosynthesis. About 0.1–1% of the total energy from the sun is absorbed by plants in this way. The element phosphorus is crucial for this process. In plants, at the molecular level, phosphorus is taken up one ion at a time to form adenosine triphosphate (ATP). The adenosine radical rotates and, using the sun's energy, picks up one phosphate ion in turn to form, progressively adenosine monophosphate, adenosine diphosphate and adenosine triphosphate. In organisms that eat the plant, the ATP rotates in the opposite direction giving off one phosphate ion at a time and releasing energy in the process. This is the world's smallest motor and it drives all living processes.

Plants use about half the energy from the sun for their own metabolic purposes. The balance is stored as chemical energy in ATP. Many animals that derive their energy in this way consume plant tissues (both living and dead). Only a small number of micro-organisms living at ocean depths and deep below the surface do not derive their energy this way. These are anaerobic organisms that obtain their energy from chemical sources. They are the descendants of species that existed billions of years ago, before there was any free oxygen or photosynthesis. They are attributed with creating the atmosphere that enabled life, as we know it, to evolve.

Organisms that derive their energy from living plant tissues are generally referred to as herbivores. All herbivores have evolved special relationships with the plant species on which they feed. For example, grass and ungulates have evolved together, as have insects and flowering plants. They depend on each other for propagation (and hence survival) and are thus in sustainable, mutually dependent relationships.

Finally, some animals, such as reptiles, derive energy directly from the sun and spend considerable time sunning themselves to reach temperatures optimal for their metabolism.

Species that derive their energy from herbivores rather than plants are generally referred to as carnivores. Again, predator–prey models are showing a high degree of sustainability and mutuality in these relationships. Organisms that derive their energy from dead tissue are generally referred to as decomposers.

The diagram shows three kinds of energy involved in natural energy processes: electromagnetic radiation, and chemical and heat energy. When completed for a local area, it provides baseline of natural energy flows that will enable anthropogenic energy impacts to be mapped and placed in a local context.

Diagram 3 — Energy and human technology

Diagram 3, like Diagram 2, is no more than conceptual at this stage. Future work will refine it to illustrate actual energy flows through a local area. Diagram 3 depicts the energy flows through the human economic system.

Although not yet illustrated, a diagram showing the evolutionary development of human technology will also be developed. This will illustrate that about half a million years ago, early humans (*Homo erectus*) started using fire. These people found a way to take the energy stored in the wood and other dead plant material and release it in a controlled way for human purposes. Uses of this technology include: keeping warm, cooking, flushing out prey and what is sometimes called 'firestick farming' or using fire to clear out undesirable species and encourage more desirable ones.

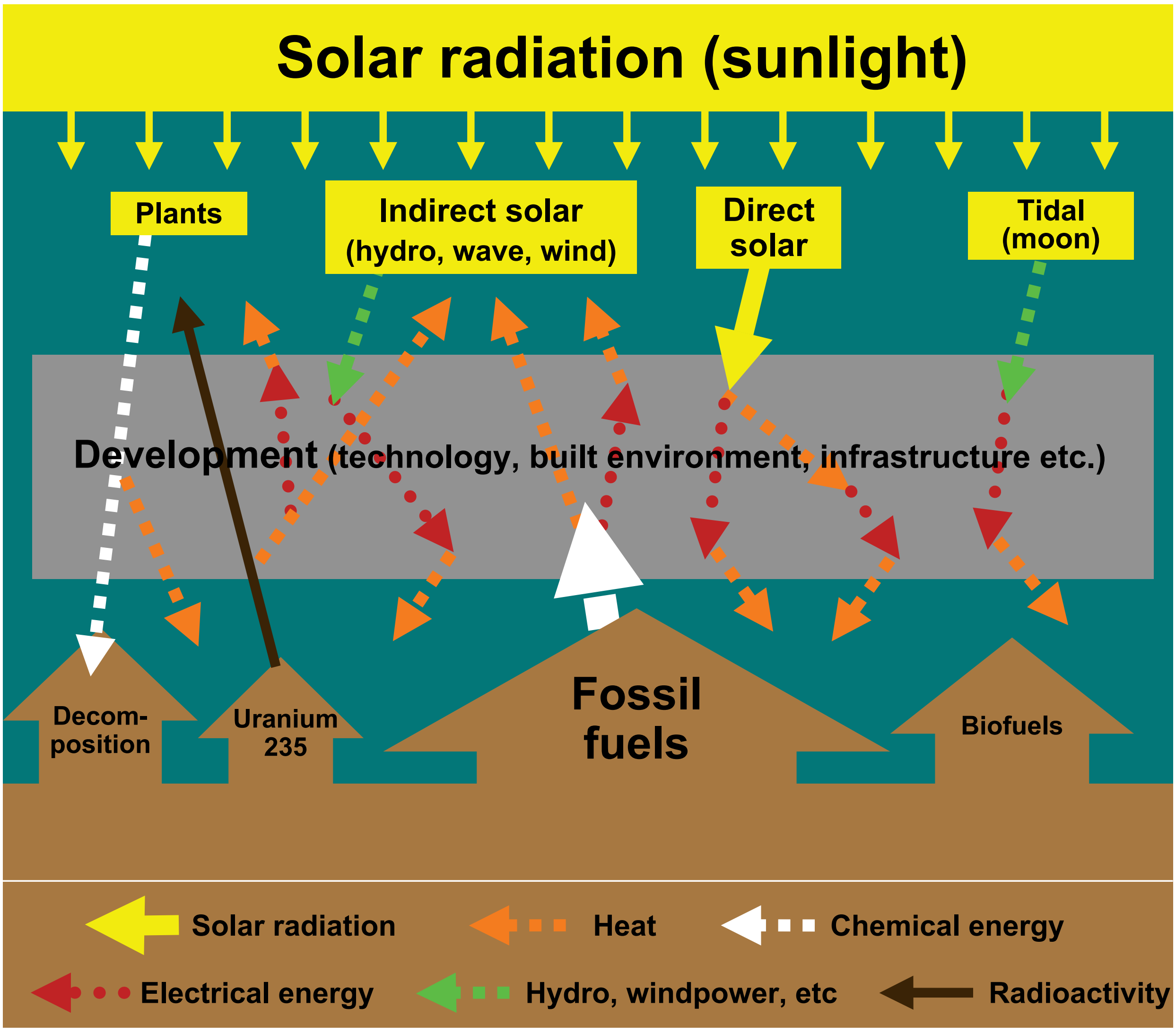


Diagram 3. Materials and energy flows through the built environment

Before then, a typical early human would have available only the energy from their own metabolism: roughly about the same amount of energy per day as flowing through a 100-watt light bulb. The use of fire more or less doubled the amount of energy available per person.

Our own species (*Homo sapiens sapiens*) has been using fire for as long as we have been recognised as a separate species: about 100,000 years or 4000 generations.

Around 10,000 years ago (400 generations) some humans abandoned their nomadic way of life and started farming. This happened in a number of places — in the Middle East, the Americas and in Papua New Guinea — apparently independently of each other. (In the case of PNG there is evidence that farming might have started much earlier.) At this time, the global human population was about 5 million people. Farming involved additional energy derived from domestic animals, particularly in ploughing and transport, and enabled substantial increases in populations. Most significantly, abandoning nomadic lifestyles and the additional food supplies freed up people from hunting and gathering to allow specialisation and the emergence of villages, towns and, ultimately, cities.

In energy terms, the next most significant development came with the industrial revolution (about eight generations ago). The discovery of fossil fuels, the various sorts of internal combustion engine and the discovery of electricity were principal drivers of this. Technology, coupled with advances in public health, led to a current population of 6 billion people. Current projections are for the human population to stabilise at around 10–11 billion over the next 50 years.

In Australia, we are now using 40 times as much energy per person as people in some less-developed countries and three times as much as we were using in the 1940s. Australian energy consumption per capita has doubled since 1960.

Diagram 4 — Energy efficiency

The energy efficiency diagram (Diagram 4) tries to capture, diagrammatically and quantitatively, the losses in energy as it is transformed from one type to another in generating and transporting through the grid. Although not illustrated, losses can be shown for petrochemical and other energy sources.

In the foregoing example, there are losses when the potential heat energy in coal is turned into steam and further losses when the steam drives the turbines. There are losses in the generators producing the electricity and in the high-voltage transmission lines. The reason voltages are so high is to minimise transmission losses.

But then there are further losses in substations where the high voltages are stepped down for domestic and industrial consumers.

Consumers are being encouraged to look for their own energy efficiencies (co-generation and factor 4 approaches for example). But, as the diagram illustrates, the losses through the total system are enormous. While there is a substantial effort in research on superconductors to try and minimise and even eliminate transmission losses, these are still a long way off. Thus, systems redesign, rather than consumer behavioural change alone, is necessary.

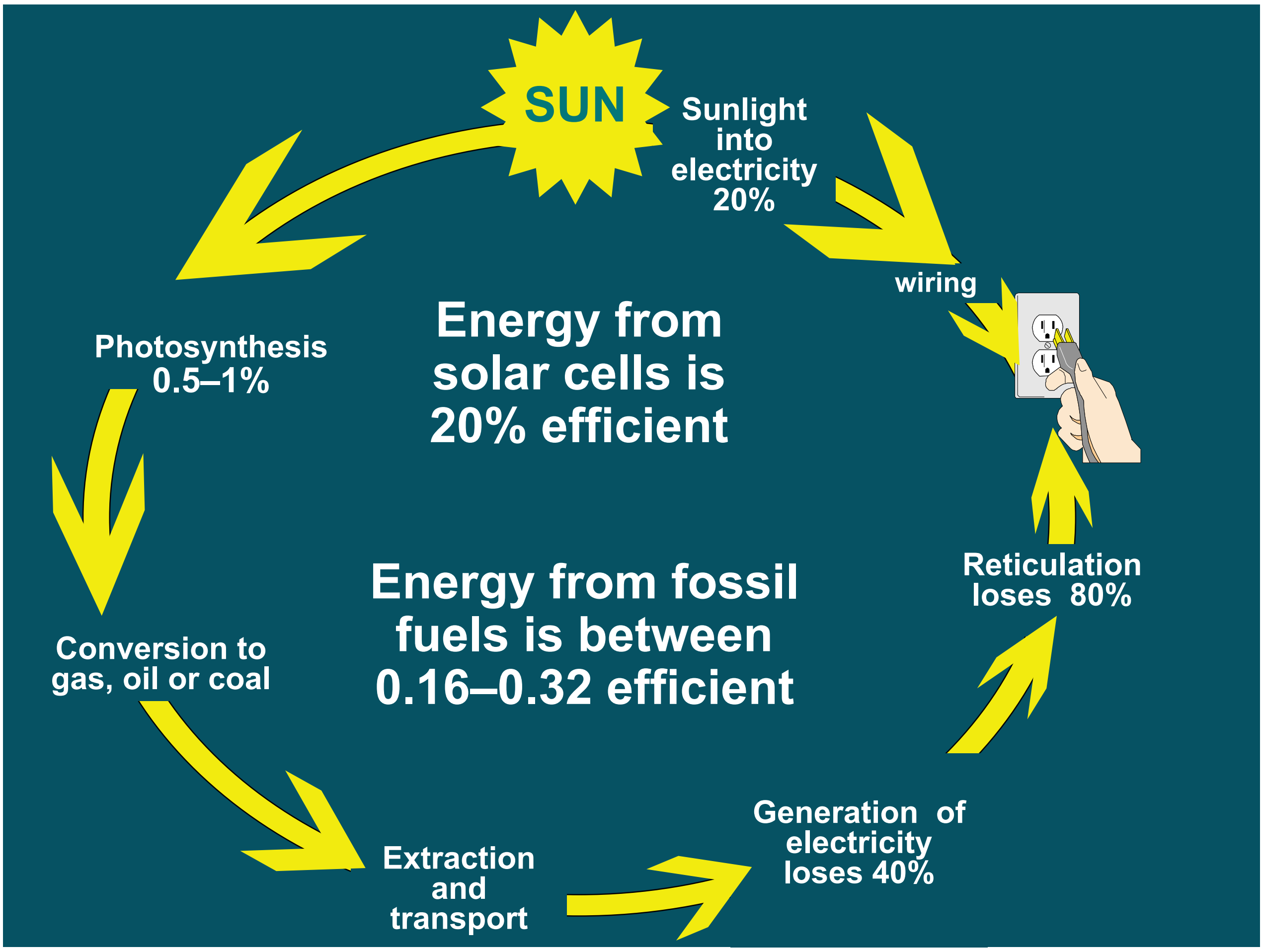


Diagram 4. Energy efficiency cycle

In the meantime, measurements of energy and predictions of future requirements are based on this extremely inefficient system. These underpin arguments that alternative and locally produced energy sources can never generate the amount of energy required to meet current, let alone future, energy requirements. The diagram aims to illustrate the fallaciousness of this argument. Leakages and inefficiencies can be eliminated by locally based energy systems using alternative energy sources. A whole-system change that will be far less leaky and inefficient than our current centralised systems is called for. In addition, breakdowns in a more decentralised system will have less impact, be less vulnerable to civil disturbances and have many other advantages that have been pointed out by proponents of solar energy.

Diagram 5 — Carbon

Diagram 5 is also conceptual and presents some global data for illustrative purposes. Further work will make it applicable to specific regions and identify specific local flows.

At this stage we have presented it in two parts: one considering only the terrestrial carbon stocks and the other oceanic stocks. Flow data have not yet been added, but even without flow data the diagrams are useful for communication purposes.

Estimates vary, but the biomass (for all living organisms) underground exceeds that above ground and, as a general rule, the surface area of plants below ground exceeds the surface area above ground. Very little known about the interaction of below and above-ground ecosystems, but it is becoming clear that this is an area in which new knowledge is urgently required, especially in the context of future carbon trading.

The quantum of carbon in the atmosphere as carbon dioxide (CO_2), methane (CH_4) or particulate matter (soot) accounts for about a quarter of the greenhouse effect. The remaining three-quarters is due to water vapour.

The approximate magnitudes of carbon stocks in gigatonnes (Gt) are as shown in Table A2. This table does not include carbon locked up in rock or the Earth's crust.

Anthropogenically released carbon is about 7 Gt per year globally. There are considerable local variations in the levels of CO_2 (and other greenhouse gas) emissions. Deciduous trees emit a lot of carbon at the time of leaf fall and their subsequent decomposition that is counteracted during the spring growth period. In Australia, land clearing is a source of local emissions along with urban areas and transport corridors.

Current direct data are available, but need considerable interpretive work to enable estimates to be made at the local level. Concern about carbon emissions and the possibility of carbon trading are generating a growing literature in this area as well as some emerging measurement conventions whose validity can be tested using MFA techniques.

Table A2. Global carbon stocks (Gt) (from Tucker and Justice 1981)

Location	Carbon stock (Gt)
Deep ocean (below 1000 m)	31,000
Fossil fuel and shale	2,000 (60% of which is potentially recoverable and if used would add 7200 Gt to the atmosphere)
Ocean thermocline (80–1000 m)	6,600
Biosphere (slow release)	1,600
Atmosphere	702
Ocean surface (0–80 m)	580
Biosphere (fast release eg. plant leaves and stems)	160
Total	**52,642**

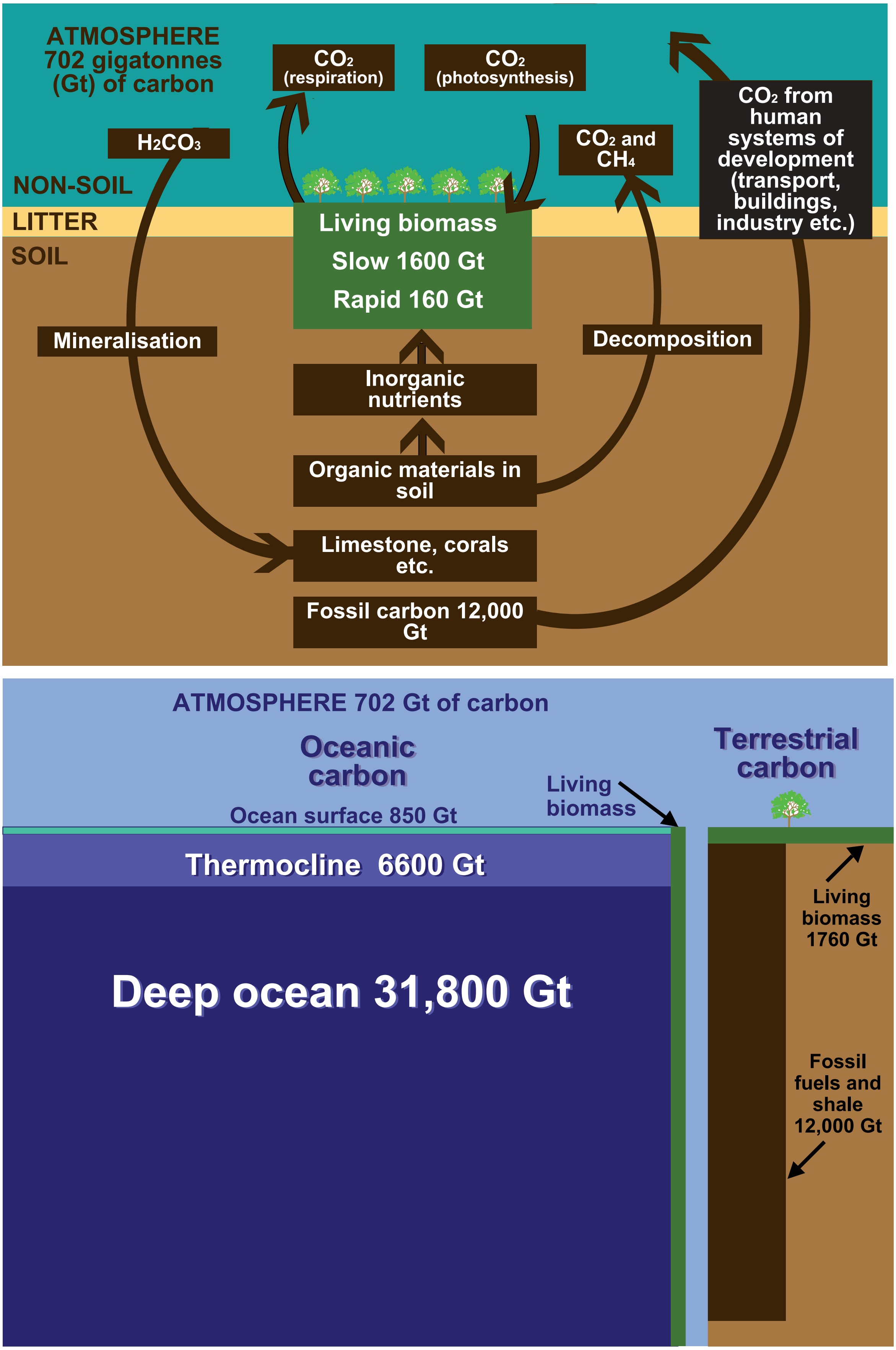


Diagram 5. The carbon cycle

Diagram 6 — Phosphorus

Australian soils generally contain low concentrations of plant-available phosphorus compared with Europe where our farming methods originate. These farming methods are often proffered as explanations for many environmental problems (as illustrated in later diagrams).

Phosphorus levels in Australian soils have been well documented and vary greatly from areas such as the Darling Downs where they are well above European averages, to the rangelands where they are well below. Much of the existing phosphorus is in the remains of decaying plant matter or bound with iron–aluminium silicates.

Phosphorus in waterways (where it can cause algal blooms) is principally due to soil erosion. Depending on the catchment, estimates range from around 50–80% of from that source. Agricultural rural run-off picks up unused fertiliser and is the second-most important source, followed by urban sewage. Detergents are almost negligible in the amount of phosphorus they add to the system. Despite this, considerable effort is being put into changing consumer behaviour (which contributes negligible amounts) when it is a whole system where change is required. This is a design problem, not a behaviour problem.

As pointed out in the main report, a major loss of phosphorus is through the export of commodities, particularly grains and meat. This phosphorus finishes up in the sewerage systems of other countries and would need to find its way back to Australia in one form or another if Australian agriculture is to be sustainable in the long term.

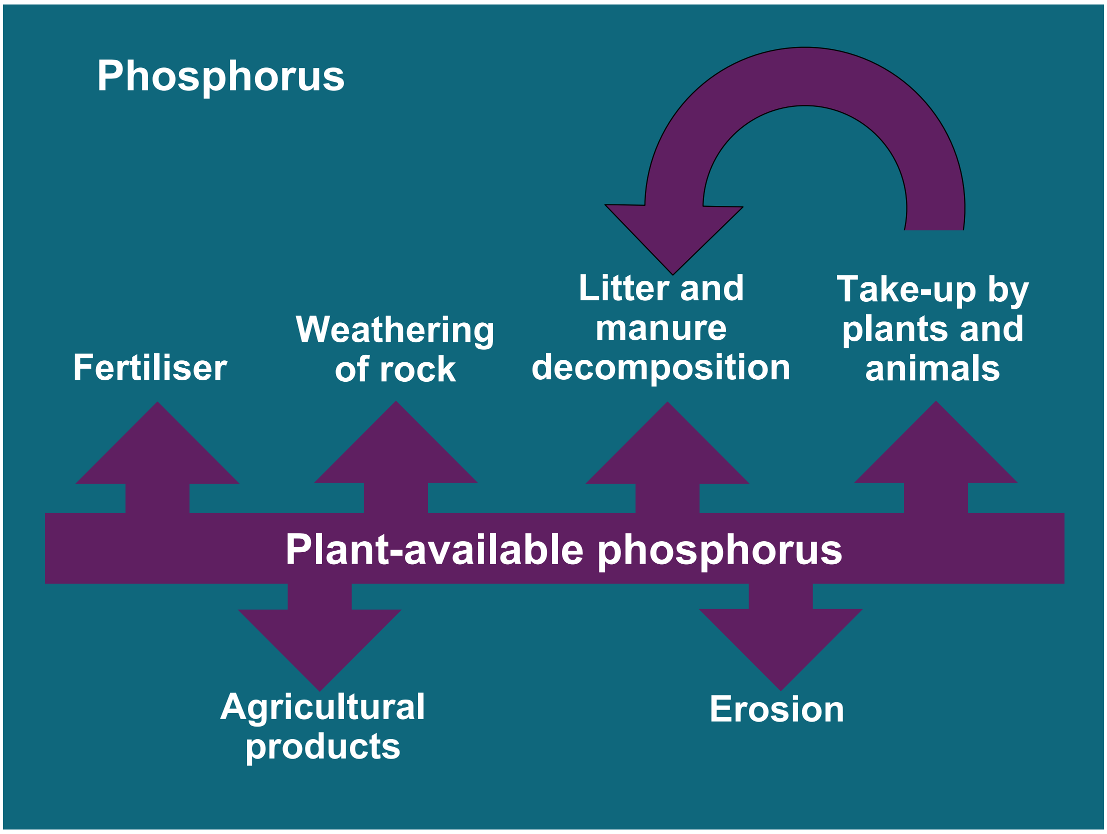


Diagram 6. The phosphorus cycle

Diagram 7 — European farming practices

Diagram 7 shows some of the well-documented ecological effects of agriculture in Australia. It shows the inherent interconnectedness and complexity of the 'problem areas'. Each of the eight issues is connected with arrows that could be described as strongly causal links demonstrated within various disciplinary frameworks. They do not represent flows. The resulting complexity is used to illustrate the difficulties decision-makers have in coming to grips with the complexities due to the narrow discipline-based approach to scientific research. A more integrative approach is shown in Diagram 8, which deals with soil structure.

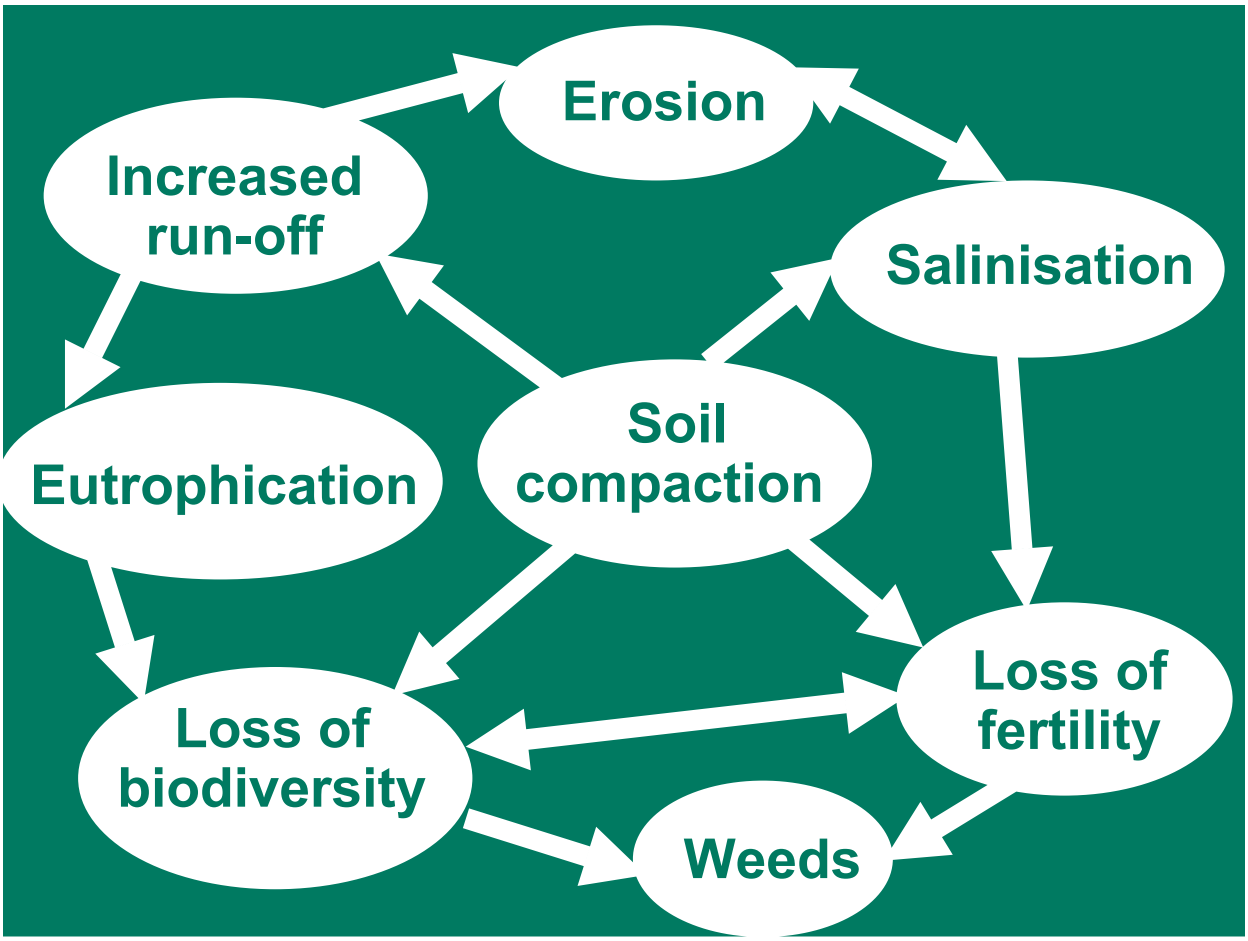


Diagram 7. European farming practices and related problems

Diagram 8 — Soil structure

Soil structure is measured as a volume-to-mass ratio (ie. a density or porosity measure) which is presented as a first approximation by the depth of soil.

Clearly more work is needed. The central idea is that the sponginess of the soil and the greater the depth of this spongy material, the more water it holds. The retained water reduces run-off, erosion and nutrient loss, reduces leakages to the watertable (and hence salinity) and, in terms of agricultural inputs, reduces the need for irrigation and fertiliser.

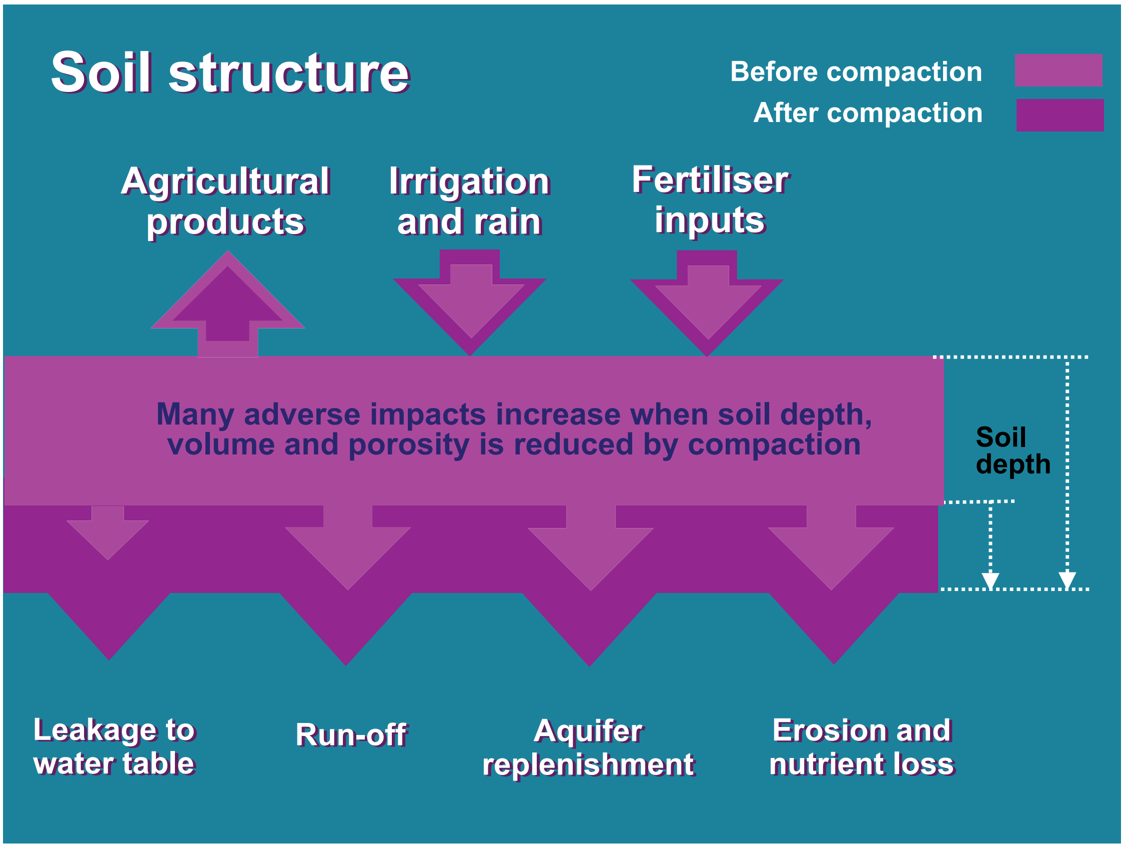
The key to soil structure is the presence organic matter and a healthy subterranean ecosystem, rich in living soil organisms that provide a range of ecosystem services to optimise natural system functioning and agricultural performance. Work on understanding and enhancing soil ecosystems is still in its early stages and will require a substantial paradigm shift away from the mechanistic chemical additive approaches.

As explained in the body of the report, this shift can be achieved in win–win ways where the cost of waste disposal and artificial fertilisers and savings in environmental clean-up costs will more than offset the shift to sustainability.

Diagram 8(b) links the key problem areas identified in Diagram 7 to the soil structure hypothesis developed in Diagram 8(a).

This hypothesis spans a number of disciplines including agricultural science, hydrology, ecology and soil science. To prevent the loss of soil structure and, where possible, encourage a return to former levels, requires the maintenance and build-up of soil organic matter, which is the basis of the soil ecosystem, and the prevention of soil compaction by stock, farm machinery and intensive cultivation practices.

(a)



(b)

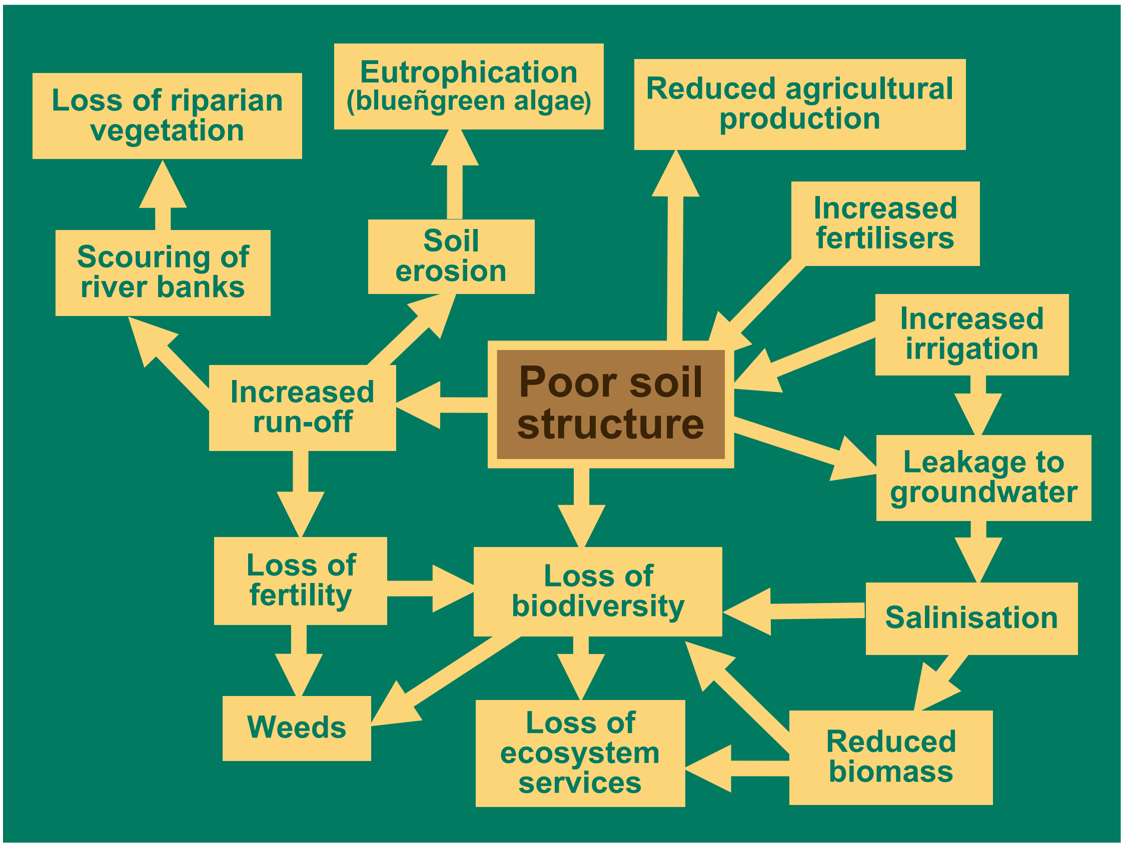


Diagram 8. Soil structure relationships

Titles in this series

Opportunities to breed/select/bioengineer plant species to control deep drainage and nutrient leakage

Biotechnology (GMO) issues and research priorities in natural resource management

Mapping regional metabolism: a decision-support tool for natural resource management

Documenting the concepts of the 'Ecosystems Farm Management' approach

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