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Material budgets as an organising framework

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Contribution to Methods Development for the National Land and Water Resources Audit

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Summary:

Material budgets offer an organising principle for information about biophysical attributes and processes in the Land and Water Audit, by providing verifiable measures of the ongoing sustainability of the land and water resources of the nation.

The approach in this Methods paper is different to that adopted in others, because the single method proposed is a conceptual framework rather than a technique or group of techniques for gathering information[1].

For a material such as water, carbon, or a nutrient, the material budget is a statement of the balance between three kinds of term: the *change in store* of the material within a region on a landscape; the *flows* of the material through the boundaries of the region; and the creation or destruction of the material within the region by chemical or biological *transformations*. Maps of material budgets can be produced at any spatial coverage from a small landscape element up to the continent, and at any spatial resolution consistent with data availability and process understanding. Material budgets are derived in practice from a combination of data, analysis and application of process models.

When appropriately constructed and interpreted, material budgets can be used in the Audit:

- *to connect* ***state*** *and* ***change*** – by providing a quantitative, spatially resolved connection between 'snapshot' assessments of landscape states, and estimates of trends or changes in response to both natural and human-induced influences;
- *to rank 'natural' and 'human-induced' processes* – by distinguishing major from minor influences on landscape state, in a spatially resolved way;
- *to measure 'landscape health' or 'catchment health'* – by providing quantitative measures of the biophysical aspects of these elusive notions;
- *to link directly with economic analyses* – by quantifying biophysical resources, and their changes, in a way which links directly with resource economics.

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[1] The headings used in the paper are different in detail from those suggested for Methods papers, as the suggested headings are linked to specific issues, processes, practices, or problems. We have endeavoured to follow the format as closely as possible, but departures have been necessary to present a clear case.

1. Overview of Material Budgets

1.1 Main Issues for Material Budgets

(a) Introduction

Material budgets offer an organising principle for information about biophysical attributes and processes in the Land and Water Audit, by providing verifiable measures of the ongoing sustainability of the land and water resources of the nation. For a material such as water, carbon or a nutrient, the material budget is a statement of the balance between (1) the *change in store* of the material within a region in a landscape; (2) the *flows* of the material through the boundaries of the region; and (3) the creation or destruction of the material within the region by chemical or biological *transformations.*

Material budgets can be produced at any spatial coverage from a small landscape element up to the continent, and at any spatial resolution consistent with data availability and process understanding. A spatially resolved material budget can be visualised as a set of maps showing the amounts of material stored within selected regions or grid cells, the changes in these stores over a selected time period, and all the flows and transformations contributing to the storage changes. Material budgets are derived in practice from a combination of data, analysis and application of process models.

Some of the flows and transformations entering a material budget will be natural, and some will be management-induced. The budget provides a way of quantifying the relative magnitudes of these influences, and of relating them to the overall resource store. Thus, budgets provide a framework for answering questions such as ‘Are we mining our natural resource assets?’ in a spatially resolved way.

A Land and Water Audit component on material budgets will not generate data in its own right. Rather, it will provide an integrating framework bringing together both existing data and information from Audit components on soils, vegetation, sediments, catchments, salinity, carbon, land use and others. Some of these, such as the components on sediments and associated nutrients (Prosser 1998), carbon (Barson 1998), water use (Roberts 1998), soil quality (McKenzie *et al.* 1998) and salinity (Nulsen and Evans 1998) may involve material budgets within their own spheres of interest. Given appropriate coordination and interactions, these will link naturally to the overall considerations of material budgets suggested here.

(b) The role of material budgets in the Land and Water Audit

Connecting states and changes: A major focus for the Audit is the relationship between the present biophysical ***states*** of landscapes and the ***changes*** leading to altered states at some future time. This provides a means of assessing the land and water resources of the nation under realistic future scenarios, or trajectories under which landscapes might change under both natural influences and alternative possible management strategies.

Figure 1 is a development of a diagram from Creighton and Young (1997) and Grayson *et al.* (1998), intended to clarify the various processes acting on a landscape or land system in its evolution from a present to a future state. Landscapes are acted on by a combination of natural and human-induced biophysical processes (both shown by red arrows). The human-induced processes, stemming from both deliberate management decisions and inadvertent actions, are strongly linked with government policies, societal values, social factors and the national and global economies (the blue arrows). These factors are explored in other parts of the methodology for the Land and Water Audit.

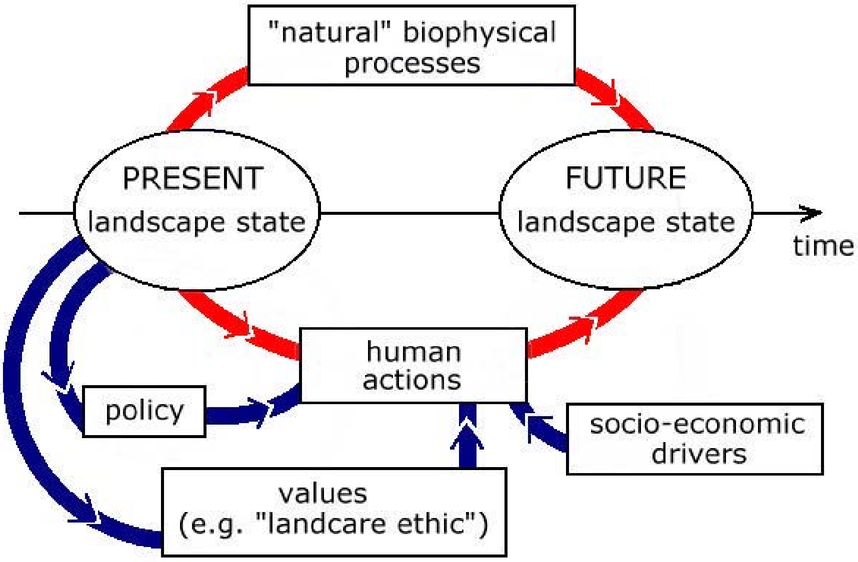

Figure 1: Processes acting on a landscape in its evolution from a present to a future state. Red (or grey) arrows indicate biophysical processes (either natural or human-induced) which can be clarified by a focus on material budgets. Blue (or black) arrows indicate policy, social and economic interactions that drive both deliberate and inadvertent human-induced biophysical processes.

The role of an Audit component centred on material budgets is to provide spatially resolved measures of the biophysical (red-arrow) links in Figure 1. This can be seen as analogous to the role of financial budgets in providing measures of the viability of an enterprise. One could regard an instantaneous assessment of the land and water resources of the nation as equivalent to the cash position. A consideration of material budgets, on the other hand, provides a view not only of instantaneous resource assets but also of how these resources are changing as a result of the full set of flows and transformations acting upon them. The resulting picture is therefore analogous to an accrual financial budget.

Outcomes: For the Land and Water Audit, a material budget framework offers –

- *Measures of biophysical sustainability:* Material budgets provide a measure of the biophysical sustainability of the land and water resources of the nation, by –
    - ◊ *Connecting landscape state and change:* quantifying the connections between the biophysical state of a landscape and the processes (natural and human-induced) causing changes in landscape state;
    - ◊ *Ranking processes* – distinguishing major from minor influences on landscape state on a range of time scales;
    - ◊ *Connecting processes* – quantifying the effects of interactions between different landscape processes.

- *Consistency checks on Audit estimates of on-site and off-site processes:* Material budgets provide connections and consistency checks on estimates of both on-site and off-site processes. Estimates are thereby improved, and a means of quality control or uncertainty estimation is provided. These consistency checks can be made in two ways:
    - ◊ *Fluid transport processes* (in both water and air) mix materials over large spatial areas and thus integrate processes contributing to material fluxes into the water or air. Measurements of material concentration changes in water or air thus provide a constraint on material budgets at large scales. In water, this check is available through river flows and sediment, nutrient and contaminant loads. In air, a similar approach is being applied with the aid of atmospheric models (see later).
    - ◊ *Consistency between different budgets* provides a spatially resolved constraint or internal consistency check. For example the water and carbon budgets interact because water is an essential resource for accumulating plant carbon, and plant carbon controls the transpiration term in the water balance. The relevant terms in these budgets must therefore be consistent in a spatially explicit way.

- *Links with economic analyses:* Material-budget analyses of biophysical states and resources provide an interface with economic analyses, by two routes:
    - ◊ Biophysical resources can be ascribed monetary values by the methods of resource economics. Therefore, states and changes in biophysical resources can be placed in an economic context once the pool sizes and their rates of change are quantified through material-budget analysis. The processes leading to changes in pool sizes also become visible to a comprehensive economic analysis.
    - ◊ The consequences of both deliberate land management decisions and inadvertent human influences can be assessed and ranked as direct terms or modifications to terms in material budgets. The impacts of these actions on material resources can thus be better defined, and in particular can be ranked against each other. This contributes to an understanding of the feedbacks and interactions between human actions and biophysical state, and thence to better land management.

- *Identification of weaknesses:* With proper uncertainty estimation, material budgets elucidate the gaps in the data, methodologies and concepts needed to determine current and future trajectories of the natural resource base, using both existing information and data generated within the Audit.

1.2 Spatial importance of material budgets in Australia

Details will be given later in Section 2.2, where present information on Australian material budgets is summarised after outlining the basic principles of material budgets in Section 2.1.

1.3 Sources of information on material budgets and their economic significance

See Section 2.2.

1.4 Costs and benefits of material budget analysis

See Section 2.2. Because a material budget is a conceptual approach rather than an issue or land degradation problem, a benefit–cost analysis is similar to a benefit–cost analysis of the entire Audit. As pointed out above, material budgets provide a rigorous means of linking biophysical processes with resource economics.

2. Understanding Material Budgets

2.1 Basic principles of material budgets

This section sets out the main conceptual ideas that underpin a material budget analysis of land and water resources at scales from paddock to continent.

(a) Definition and examples

A material budget is a statement of the balance between the storage changes, flows and transformations of some material within a defined *control region*, such as the top 5 metres of soil across a specified land area. The choice of control region is discussed in more detail below. The three types of term appearing in the material budget are:

- the *change in store* of the material within the control region, quantified as the change per unit time of the stored mass S of material within the region;
- the *flows* of material through the boundaries of the control region, quantified as a set of fluxes F_i where the subscript i distinguishes different fluxes; and
- the *transformations* of material within the region by biological and chemical processes, quantified as a set of source or sink strengths T_j distinguished by the subscript j, with T_j being positive for sources and negative for sinks.

Over a time interval Δt between times t_0 and t_1, the balance between these terms can be written generically as:

$$\Delta S/\Delta t \quad = \quad (S_1 - S_0)/(t_1 - t_0) \quad = \quad \Sigma F_i \;+\; \Sigma T_j \qquad (1)$$

where $\Delta S = S_1 - S_0$ is the difference between the store contents S_1 at time t_1 and S_0 at time t_0. The summations extend over all processes contributing to fluxes and transformations, respectively. Equation (1) also provides natural averaging[2], spatially over the control region and temporally over the interval Δt.

Budgets of the form of Equation (1) can be constructed for any material which undergoes transport (represented by F_i) or transformation (represented by T_j) on a landscape, for example: water, carbon, nitrogen, phosphorus, sulphur, potassium, sodium, other metal ions, protons (acidity), soil or sediment, pesticides, herbicides, pollutants and energy[3].

Fundamental examples are provided by the soil water budget and the carbon and nitrogen budgets (including plant and labile soil pools in both cases). Over a land region, these balances can be written schematically as:

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[2] Formally, each flux F_i is the integral of a flux density over the contributing boundary area, and each transformation term T_j is the volume integral of a source strength over the volume of the region. Also, F_i and T_j are time-averaged over the interval between t_0 and t_1.

[3] The surface energy budget is the balance between radiative energy input, heat transfer to the atmosphere by both sensible (direct) and latent (evaporative) exchanges, and heat storage changes in the ground. Although energy is not a material entity, it obeys thermodynamic conservation principles and can be described by a conservation equation of the generic form of Equation (1).

$$W_1 - W_0 = \text{[rainfall]} - \text{[runoff]} - \text{[transpiration]} - \text{[soil evaporation]} - \text{[drainage]} \tag{2}$$

$$\begin{aligned} C_1 - C_0 = {} & \text{[assimilation]} - \text{[autotrophic respiration]} - \text{[heterotrophic respiration]} - \\ & \text{[herbivory]} - \text{[burning]} - \text{[harvesting]} \end{aligned} \tag{3}$$

$$\begin{aligned} N_1 - N_0 = {} & \text{[fertiliser application]} + \text{[microbial fixation]} + \text{[atmospheric deposition]} - \\ & \text{[gaseous losses to air]} - \text{[leaching to groundwater]} - \text{[net loss by waterborne} \\ & \text{sediment transport]} - \text{[net loss by windborne sediment transport]} - \\ & \text{[herbivory]} - \text{[burning]} - \text{[harvesting]} \end{aligned} \tag{4}$$

where W is the soil water store in the root zone (usually expressed as volume per unit land surface area), and C and N are the terrestrial stores of carbon and nitrogen (expressed as mass per unit land area). The terms on the left hand side are storage changes, and the terms on the right are a mixture of vertical fluxes, horizontal fluxes, and transformations.

(b) Choice of control region

The choice of control region selects the processes incorporated in the material budget, and is therefore of critical importance. The *vertical* extent of the control region is usually defined to span one or more of the functional layers of the terrestrial biosphere. In approximate descending order of height, these layers include (1) the *lower atmosphere* (from the land–air interface to a convenient height such as the top of the daytime convective boundary layer or the top of the troposphere); (2) the *land–air interface* itself (strictly, a very thin layer of complex shape, encompassing the land–air interface); (3) the *plant zone* (the region of complex geometry which is physically occupied by plant material); (4) the soil *root zone* (between the soil surface and the root extraction depth); (5) the *unsaturated zone* above the water table; and (6) the groundwater or *saturated zone* (bounded below by bedrock). It is possible to define the vertical extent of a control region using any contiguous group of these biophysical layers, for instance a layer including the soil root zone, the plant zone and the lower atmosphere.

The *horizontal* extent of the control region may vary from a narrow column up to the continent or even the globe. Common choices are (1) a single, horizontally homogeneous patch of landscape, such as a uniform part of a paddock; (2) a catchment; (3) a stretch of river; (4) a major drainage basin such as the Murray–Darling Basin; (5) a large region with convenient arbitrary boundaries such as lines of latitude and longitude; (6) the continent; and (7) the earth (for example, the global atmospheric carbon budget).

For example, Equation (2) is based on a control region extending vertically through the soil root zone, while in Equations (3) and (4) the control region extends vertically through the sum of the plant and soil root zones. In each case the horizontal extent of the control region can be a single horizontally homogeneous patch of landscape, or a combination of patches.

A common approach in the choice of control region is to make its boundaries coincident with as far as possible with physical boundaries through which there is no mean flow, to simplify the evaluation of fluxes due to fluid transport. The simplest example is a catchment, where lateral water movement occurs only through the exit stream. Other examples occur when the side boundaries of the control region coincide with streamlines in the flow of the transporting fluid (either water or air), since there are no fluxes due to mean flow across boundaries which are coincident with streamlines; for instance, budgets in rivers and budgets defined along ‘flowtubes’ of groundwater systems.

As the size of the control region is increased, fluxes across the boundaries of small-scale sub-regions become internal transfers within a larger region and therefore cease to appear explicitly in the budget. For example, no terms appear in both Equations (3) and (4) for the transfer of carbon or nitrogen between plant and labile soil pools, as both pools are within the chosen control region.

(c) Interconnected nature of material budgets

There are basic connections between many material budgets. These are of several kinds: first, chemical and biological transformation processes represent a sink for one entity and a corresponding source for another within the same region. Second, some energetic processes appear in both the surface energy balance and in material budgets, the core example being the latent heat flux in the energy budget which also appears as the sum of the transpiration and soil evaporation terms in the soil water balance. Third, many processes involved in fluxes and transformations are correlated because they are driven by similar external forcings such as the availability of basic plant resources (light, water and nutrients). Such processes tend to have similar spatial and temporal behaviours: a simple example is offered by assimilation and transpiration in conditions where water use efficiency does not vary greatly. Finally, flows across adjoining boundaries of contiguous control regions appear with opposite sign in the budgets for each region.

2.2 Existing information on material budgets

(a) Water budget

Overviews of the time-averaged, spatially aggregated, continental-scale water budget are presented in McMahon *et al.* (1992) and SoE (1996), including discussions of diversions of water resources for human use. The amount of water available terrestrially for agriculture and ecosystems must be assessed by more spatially disaggregated approaches, utilising spatially resolved data on precipitation, runoff and evaporation. These data are available to varying degrees of spatial resolution, temporal resolution and reliability.

- *Precipitation:* Elevation-based statistical interpolation techniques developed by Mike Hutchinson, Wolfgang Cramer and colleagues have led to the availability of mean (annual and monthly) precipitation and temperature, globally at a resolution of 0.25 deg and over the Australian continent at finer resolution: see Figure 2. Ten-day precipitation time series are also available.
- *Runoff:* basic data on runoff from major Australian drainage basins (AWRC 1985; SoE 1996; Figure 3) have been combined with similar data from other nations and simple topographically based models to produce a 1 deg global mean annual runoff map (Cogley 1994; Figure 4). While this map is far too coarse to be appropriate for the present work, it defines both a requirement (a much finer spatial resolution) and an approach (terrain analysis methods related to, but different from, those used to produce Figure 2). The climatic-mean Australian continental water balance, defined from continental averages of precipitation P (Figure 2), runoff R (Figure 3) and evaporation (estimated as $E = P - R$) is shown in Figure 5, together with the global terrestrial average water balance and the

balance for several other continents. This highlights the fact that Australia is quite anomalous: the runoff R is only 10% of P for Australia, in comparison with a global terrestrial average of about 40% .

- *Evaporation and soil moisture:* Direct, spatially resolved measurements of evaporation and soil moisture are not available, so process models must be used to both these terms in a spatially resolved water balance for the soil root zone. Fortunately, a number of models are available for the root-zone soil moisture and the fluxes which control it. The data requirements typically consist of meteorological data (particularly precipitation, radiation and temperature, with humidity and wind speed either from data or surrogates); soil data (depth, texture) and vegetation data (type and amount). As examples of the type of results now available, Figures 6 and 7 show monthly averaged evaporation for 1987 and the annual-averaged difference between 1988 and 1987 (Raupach *et al*. 1998). The predicted continental-average evaporation over both years is close to the climate-average estimate inferred by a quite different route in Figure 5.
- *Deep drainage:* One term which presents difficulty within modelling framework used in Figures 6 and 7 is the deep drainage term. This is often (though not always) a small flux relative to the other fluxes controlling the root-zone moisture, so a rough estimate often serves to characterise the root-zone moisture quite well. However, it is a dominant flux for the layers below the root zone. Therefore, questions such as the role of deep drainage in groundwater dynamics require a different conceptual framework, based on the material budget for water in the zones below the root zone rather than the root zone itself.

In summary, it is possible to obtain spatially and temporally resolved information on most of the terms in the water balance for the soil root zone, using existing process understanding and data sources.

(b) Carbon budget

Studies of the continental carbon budget (in the plant zone and soil root zone) are being driven by requirements for Australia to produce verifiable inventories of greenhouse gas sources and sinks, including the contribution of the terrestrial biosphere through the gases CO_2 and CH_4 (and N_2O, a non-carbon greenhouse gas). By mass of C, over 95% of the biospheric carbon exchange is through assimilation and respiration of CO_2 (Galbally *et al.* 1992). However, the carbon budget is also central to an assessment of land and water resources for many other reasons. To name only two, carbon (in the form of biomass) is a principal economic product of the system, and biomass levels play a large part in determining land sustainability by controlling erosion.

The CO_2 fluxes in the carbon balance, Equation (3), are often expressed in terms of Gross Primary Productivity (GPP), Net Primary Productivity (NPP) and Net Ecosystem Productivity (NEP), as follows:

$$\begin{aligned}
\text{GPP} &= [\text{assimilation}] \\
\text{NPP} &= [\text{assimilation}] - [\text{autotrophic respiration}] \\
\text{NEP} &= [\text{assimilation}] - [\text{autotrophic respiration}] - [\text{heterotrophic respiration}]
\end{aligned} \tag{5}$$

Gifford *et al.* (1992) estimated the continental NPP for Australia as 2.75 GtC/yr, a figure now thought to be somewhat too high. A rough estimate can be obtained by assuming areas and typical specific NPP values for three land cover types as shown in Table 1.

	Forest	Grass	Desert	**TOTAL**
specific NPP (kgC/m^2/yr)	0.5	0.3	0.01	
Area fraction	0.1	0.3	0.6	
Area (km^2)	769 200	2 307 600	4 615 200	
total NPP (GtC/yr)	0.385	0.692	0.046	**1.123**

Table 1: Estimate of Australian NPP from assumptions about three land cover types. Values of area fraction and specific NPP assigned after discussions with R.D. Graetz and J.J. Landsberg (*pers. comm*); area of Australian continent = 7 692 000 km^2.

This compares with several other NPP estimates as follows:

Gifford *et al.* (1992)	2.75	GtC/yr
Rough estimate (Table 1)	1.12	GtC/yr
Gifford (1997, *pers. comm.*)	1.4	GtC/yr
Woodward *et al.* (1995)	0.6	GtC/yr
Global pro-rated	3.12	GtC/yr

There is clearly a significant uncertainty in the Australian NPP, but it does appear to be around 1 GtC/yr, substantially less than what would be expected if the global terrestrial NPP of about 60 GtC/yr is pro-rated to the area of Australia using the fact that the ratio of the area of Australia to the global land surface area is 0.0502. The resulting global pro-rated estimate would be 3.12 GtC/yr, about a factor of three higher than the likely true value. This difference reflects both the low rainfall and the low soil nutrient status of the Australian continent, relative to the terrestrial average.

An added difficulty is that the quantity actually required for assessment of the net greenhouse sources and sinks in the terrestrial biosphere is not NPP but NEP, an even more difficult quantity to infer. Progress in refining the terms in the carbon budget is likely to come from several sources, none of which is complete in itself. However, within a material budget framework, the whole is greater than the sum of the parts. These sources are:

- *Improved measurements of soil and vegetative carbon stores:* The Audit methods paper by Barson (1998) stresses the estimation of soil and vegetative carbon pools, and their rates of turnover. Because of magnitudes of the stores and the slowness of the turnovers, this information alone is unlikely to determine NEP with the necessary precision for greenhouse applications, but it will be a necessary and important contribution in combination with other approaches.
- *Linked models of the terrestrial carbon, nutrient, water and energy cycles:* Appropriate models of many aspects of the terrestrial carbon budget, with links to water, energy and nutrient budgets, have been developed by Potter *et al.* (1993, 1997), Landsberg and Waring (1997) and Coops *et al.* (1998), among others. These models use (mainly) remotely sensed data to infer NPP. A feature of the Landsberg–Waring–Coops approach is the simplifying assumption (supported by existing field data) that the ratio of NPP to GPP is constant at about 0.45 for forests. Similar simplifications for other ecosystems are possible, terms in the carbon cycle to be quantified in a *spatially resolved* manner. Some relevant studies are already under way in the context of global biogeochemical cycles; for example, Figure 6 shows modelled soil carbon for Australia, as part of a global field (Woodward *et al.* 1995). While this map can be criticised (for instance in probably overpredicting tropical soil

carbon), it demonstrates that starting points are available. Data to constrain and improve these estimates are available from the soil carbon work by Jan Sjkemstad and Michele Barson (Barson 1998).

- *Treatment of herbivory, harvesting, and burning:* These fluxes must be treated differently as they depend partly or wholly on human land management. Audit methods components on land use and carbon (Barson 1998) include some strategies for dealing with these.
- *Consistency with atmospheric data:* Concentrations of CO_2 or other material in an air mass are the net result of the exchange fluxes of material between land and atmosphere (discounting chemical transformations in the air itself). For example, air which has passed over the Australian continent exhibits a CO_2 concentration which is typically lower than the Southern hemisphere background observed over the oceans, because of a net terrestrial carbon uptake. Powerful global constraints on net land–air exchanges are therefore provided by measurements (both routine and in campaign mode) of atmospheric concentrations, together with knowledge of air mass trajectories and some initial constraining information about the character of the surface exchanges. This is an application of an *atmospheric* material budget, and an example of consistency checking using fluid transport processes; see Section 1.1(b), top of p. 4. In the case of CO_2, the approach is particularly significant because it determines NEP directly. It is being explored in a project by the CSIRO Biosphere Working Group, an informal multi-Divisional group working under the auspices of the CSIRO Climate Change Research Program. Close links should be maintained between the Land and Water Audit and the Biosphere Working Group, because the large-scale constraints provided by atmospheric measurements are invaluable in determining budgets of carbon and other materials at the continental to large regional scale.

In summary, many aspects of the carbon budget present challenges. However, a combination of several approaches, each acting to constrain the others, will lead to vastly improved estimates of the main terms, not only at continental scales but also at the fine spatial resolutions permitted by land use data and remote sensing observations.

(c) Nutrient (N, P, S, K) budgets

For nitrogen, phosphorus and sulphur, the present information base allows only a rough quantification of even the continentally aggregated budgets in the plant zone and soil root zone. Table 2 shows estimates of the major terms in these budgets from the excellent survey by McLaughlin *et al.* (1992). Additional information on the farm input and export of potassium and phosphorus, and their removal off-farm and off-shore in agricultural produce, has been gathered by Doug Reuter (SCARM 1997).

According to Table 2 there is a large excess of total continental inflow over outflow in each of the N, P and S budgets. The regional picture is far more complex, as hinted by the farm import and export data of Reuter (SCARM 1997). There is also evidence from trends in wheat yields and soil fertility studies of a long-term decline in soil fertility in wheat cropping areas, only just offset by agronomic and varietal improvements (Hamblin and Kynear 1993).

The approaches for improving these budgets involve similar strategies to those for carbon, together with monitoring of the farm, industry and urban components of the budgets at regional scales along the lines set out by (McLaughlin *et al.* 1992) and SCARM (1997).

Valuable constraints are provided by atmospheric and riverine material budgets, applying the principle of using fluid transport processes to provide consistency checks (Section 1.1(b)):

- Riverine flows and yields of sediments and nutrient provide constraints on the sources and sinks of these entities in catchments. Within the Land and Water Audit it is anticipated that the majority of work in this area will take place in companion projects, see especially the Methods paper on soil, land use and water integration (Prosser 1998). Similar comments apply for salt budgets, though that issue is not explored further here.
- Atmospheric measurements of nitrogenous and other gas concentrations constrain the fluxes of these gases over large regions in a similar way to the case of CO_2 described above. As in that case, links should be maintained between the Land and Water Audit and the CSIRO Biosphere Working Group.

INFLOWS (kt/yr)	**P**	**S**	**N**
Atmospheric deposition	77	769	1150
Food, fish, and timber imports	1	1	2
Fertiliser imports	380	325	380
N fixation (mainly sown pastures)			1900
TOTAL	**458**	**1095**	**3432**

OUTFLOWS (kt/yr)	**P**	**S**	**N**
Food and fibre exports	56	52	415
Urban discharge	11	77	32
Soil erosion	19	10	58
Leaching	3	87	243
Fire	4	120	1200
S: biogenic gaseous emissions		81	
N: ammonia volatilisation			334
N: denitrification			41
TOTAL	**93**	**427**	**2323**

Table 2: Terms in the Australian continental budgets of phosphorus, sulphur, and nitrogen, from McLaughlin *et al.* (1992). Wide uncertainty bands in the soil erosion and leaching terms are not shown.

One direct estimate of the economic implications of the budget figures in Table 2 can be made from the replacement cost of nutrients as fertiliser. In 1994, a typical fertiliser with an N:P:K ratio of 32:10:0 had a cost of about A$0.37 per kg (fluctuating because of market volatility and freight costs). On this basis the N outflow from the continent was worth over $2 billion, and the P outflow around $300 million. According to the material budget in Table 2, about half of the N outflow occurs by fire.

(d) Soil, vegetation and land use data

Data on soils, vegetation and land use is crucial for providing spatially resolved estimates of the water, carbon and nutrient budgets.

- *Soil data:* Within the Land and Water Audit framework, the provision of soil data is primarily within the ambit of the project on Soil Quality (McKenzie *et al.* 1998). Several existing data sets are available, beginning with the digital Atlas of Australian Soils which

provides a basic framework. There is both a need and a capability for much improved disaggregation of the information in the Atlas, using the methods of terrain analysis. Current relevant activities include the Murray–Darling Basin Soils Information Strategy (MDBSIS) and ACLEP (the Australian Collaborative Land Evaluation Program). Interpretive 'pedotransfer functions' are being developed to facilitate the translation of these descriptive data to functional physical and chemical properties (Cresswell and Paydar 1996; Paydar and Cresswell 1996; Cresswell *et al.* 1998; Bond *et al.* 1998), while the work of Jan Sjkemstad and Michele Barson (Barson 1998) will make important related contributions for soil carbon.
- *Vegetation data:* The digitised version of the Carnahan Australian vegetation map provides a starting point, but improvement is anticipated through several Audit initiatives.
- *Land use data:* As for vegetation, this is a key variable. It is important to gauge crop rotation strategies, stocking rates and other management-related variables, as these have significant impacts on material budgets and sustainability.

(e) Other budgets

The discussion has focussed on budgets of water, carbon and nutrients in the plant zone and the soil root zone. The methodology advocated here is applicable much more generally, to other entities including salt (Nulsen and Evans 1988), sediments (Prosser 1988) and pesticides (Raupach and Briggs 1997). It is also applicable in control regions other than the plant and soil root zones, including groundwater, rivers, and the atmosphere. We have alluded to both the latter two in the context of using fluid transport processes to provide consistency checks (Section 1.1(b)). Application of material budgets approaches should be a linking theme common to many Land and Water Audit projects.

3. Methodology, Approach, and Data Requirements

This section covers Sections 3 (*Comparing the Options*), 4 (*The Preferred Approach*), and 5 (*Input and Output Specification*) of the requested format for a Methods paper. In Section 2 we have presented several options for finding and constraining spatially resolved budgets for carbon, water and nutrients, at scales from those resolvable by available soil, vegetation and land use data (potentially a kilometre or less) to continental. We have argued that information from all approaches must be combined to determine and constrain material budgets effectively.

We emphasise again that a Land and Water Audit component on material budgets will not generate data, or all of the material-budget analysis, in its own right. Rather, it will provide an integrating framework bringing together both existing data and information from Audit components.

Nevertheless, there is a key role for an integrative project focussed on the linked water, carbon and nutrient budgets of the plant zone and the soil root zone across the continent. This section briefly outlines some aspects of such a project. A close relationship with other Audit components is assumed.

3.1 Objectives

By combining analyses of existing data, data assembled through other Audit initiatives and simple models of physical, chemical and biological processes, the project will provide the best possible continent-wide estimates of the major flux and transformation terms in the terrestrial budgets of surface water, soil water, plant carbon (grassy and woody), soil carbon, and soil nutrients (a preliminary indicative list being N, P, K and S, subject to further discussion). Quality assessments will be provided by consistency checks and by uncertainty assessment. Specifically, budget estimates will be checked for consistency in three ways: internal consistency through simple process models, consistency with river flows and yields of sediment and nutrient (linking with component on sediments), and consistency with atmospheric concentration measurements (see above). Uncertainty assessments will be provided for all budget estimates.

These budget estimates will be interpreted to provide the following *derived outputs*:

- quantitative, spatially resolved connections between the biophysical state of a landscape and the processes (both natural and human-induced) leading to change in landscape state;
- rankings of ‘natural’ and ‘human-induced’ processes, distinguishing major from minor influences on landscape state;
- measures of biophysical aspects of ‘landscape health’ or ‘catchment health’;
- data on the natural resource base, to quantify natural resource assets and the rates of change in those assets, under present land use and management and under selected scenarios for future changes in land use or management on a regional basis.

These outputs will provide information in their own right for policy development and for public-education purposes, and be capable of linkage with regional or national economic analyses.

The *horizontal spatial resolution* will be consistent with that of the necessary climate, soil, vegetation and land use databases. For some purposes it may be sufficient to resolve budgets spatially only to the scale of major drainage basins or biogeographic regions. For other purposes, particularly those involving the consequences of different land uses, a finer spatial resolution will be required. The resolution is likely to vary from region to region, depending on data availability, but in general should be 5 km or finer. This defines the finest horizontal extents for control regions.

The *vertical spatial resolution* will be defined by using *control regions* which vertically span the plant zone and the soil root zone (between the land–air interface and the rooting depth for the deepest rooted vegetation at any given location).

Temporal resolution will be obtained by constructing time histories of the storage change, flux and transformation terms in the budgets, initially at the time resolution required to resolve the important processes (which will depend on both process and location). Time series will be suitably aggregated (to 10-day or 30-day resolution) for analysis in two ways:

- to infer temporal statistics of the budget terms and processes (such as monthly and annual long-term means), and measures of the responses of monthly and annual means to climate variability (such as temporal standard deviations);
- to study specific events and pairs of climatically contrasting years such as 1987–88, with a focus on climatic or land-management events that lead to major budget imbalances.

The issue of *quality assessment* is critical. It is not realistic to impose absolute benchmarks for quality at the outset of an exercise such as this, because the data availability and the base of understanding varies enormously between budgets for different entities, and spatially between regions. Rather than absolute accuracy requirements, suggested quality are (1) that budgets are checked for consistency, and (2) that uncertainties are estimated rigorously, even if the resulting error bands turn out to be very large. Quantitative estimates of major terms in some budgets are relatively straightforward, for instance the surface fluxes in the soil water budget. In other cases the maximum information which can be obtained may be a ranking or a sign estimate for processes contributing to the budget, for example the relative roles in nutrient budgets of farm imports, removal by harvest and environmental transfers.

3.2 Methodology and approach

Success in this project hinges on four related factors: (1) application of appropriate models of major processes; (2) collation and use of the available information base; (3) application of methods for consistency checking; and (4) uncertainty estimation. The last two together form the means of quality assessment in the project.

(a) Process Models

The project will depend fundamentally on appropriate, simple, interconnected models for the major physical, chemical and biological processes represented by budget terms. This implies a need for elegant, economical descriptions of individual processes which can form reliable building blocks for integrated assessments. Such descriptions must respect (and may be derived from) basic principles of physics, thermodynamics, chemistry, physiology and ecology. They must also be capable of being linked, since the fundamental issues hinge on the behaviour of coupled systems. Examples of the style of model envisaged include compartment soil water balance models incorporating analytical solutions in parameter specifications; simple models for climate–landscape interactions which account for physical, physiological and convective boundary layer feedbacks (Raupach 1998); biogeochemically literate compartment models for carbon and nutrient movement (Potter *et al.* 1993, 1997); simple models of the biogeochemical consequences of landscape disturbance (Emanuel 1996); or related two-component ecological models for tree–grass interactions in savannah and semi-arid landscapes. In general, the selection of a model depends on both the required spatial and temporal resolution of the processes of interest, and also on the available data. It is likely that different models will be appropriate for describing the same process at different spatial and temporal resolutions, or in circumstances with different data resources.

(b) The Available Information Base

Already discussed in Section 2.2.

(c) Consistency checking

Consistency checks are available in three ways. One is based on the need for internal and mutual compatibility between budgets, and the other two on large-scale constraints provided by the mixing of materials in water and air, respectively.

Internally and mutual consistency within and between budgets: This requirement is enforced through the use of appropriate process models. The ability to impose such a consistency check is one main reason for studying budgets in an integrated rather than a piecemeal way. *Constraints from fluid transport processes:* Material concentrations in both water and air are the integrated result of processes over wide spatial scales, because both fluids mix material very effectively. Observations of these material concentrations therefore provide constraints on flow and transformation processes. See Section 1.1(b) and Section 2.2(b) and 2.2(c).

(d) Uncertainty estimation

The material-budget approaches outlined in this paper must necessarily operate with numerous uncertainties of varying degrees. These arise from the models used to represent physical processes; from the data used to drive the models; and from spatial and temporal variability in processes and attributes which can only be partly accounted for within a spatially and temporally discrete framework, no matter how finely resolved.

A formal analysis will be used to quantify and represent uncertainty as an integral component of the derived output from the project. This will begin by categorising the relative importance of each budget term within each control region, and will then be linked to a quality estimation of the data available to represent or constrain each term or attribute. Variables which are common to several budgets, or which interconnect budgets, will receive special attention. Account will be taken of the likely spatial and temporal variations in soil, climate and land use and management attributes. Given decisions on the importance of the terms and the quality of the information available to estimate them, process models can be tuned to match complexity (quality of process representation) to outcome certainty. A budget consisting of terms of well-defined relative significances, described by well-understood models, run using quality data, will result in a high degree of certainty in the output. In more data-poor examples, the certainty of the result will be compromised but still clearly quantified. Uncertainty in derived outputs should also be carried through into economic analyses.

3.3 Project budget

An indicative budget only is proposed at this stage. An integrative assessment as suggested here will require 2.5 dedicated staff for the period of the project, envisaged to be 3.5 years. Contributions from numerous other staff will also be required; these have not been costed in the following. A standard multiplier of 1.99 for direct salary overheads and unavoidable research costs has been assumed. Operating has been costed separately at $20k p.a.

Coordinator (0.5 position at CSOF 7.1)	$233k	(total for 3.5 years)
Modeller (1 position at CSOF 5.1)	$340k	(total for 3.5 years)
Data manager (1 position at CSOF4.1)	$288k	(total for 3.5 years
Operating ($20k p.a.)	$70k	(total for 3.5 years)
Start-up hardware and software	$50k	(once only)
Cumulative total:	$981k	

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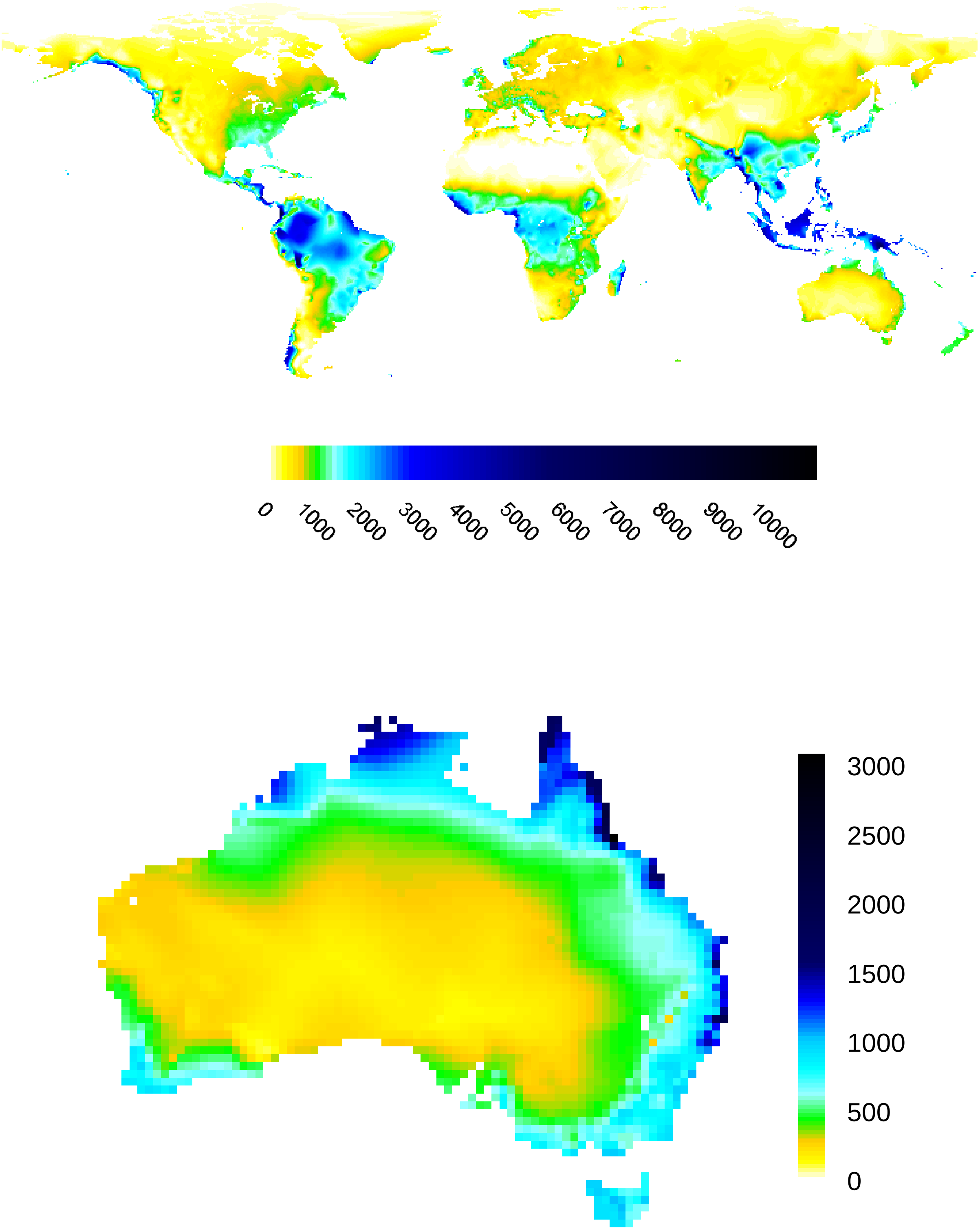

Figure 2: Global annual average precipitation gridded to 0.25deg (W. Cramer, 1997, personal communication) with Australian data set enlarged (note expanded colour scale).

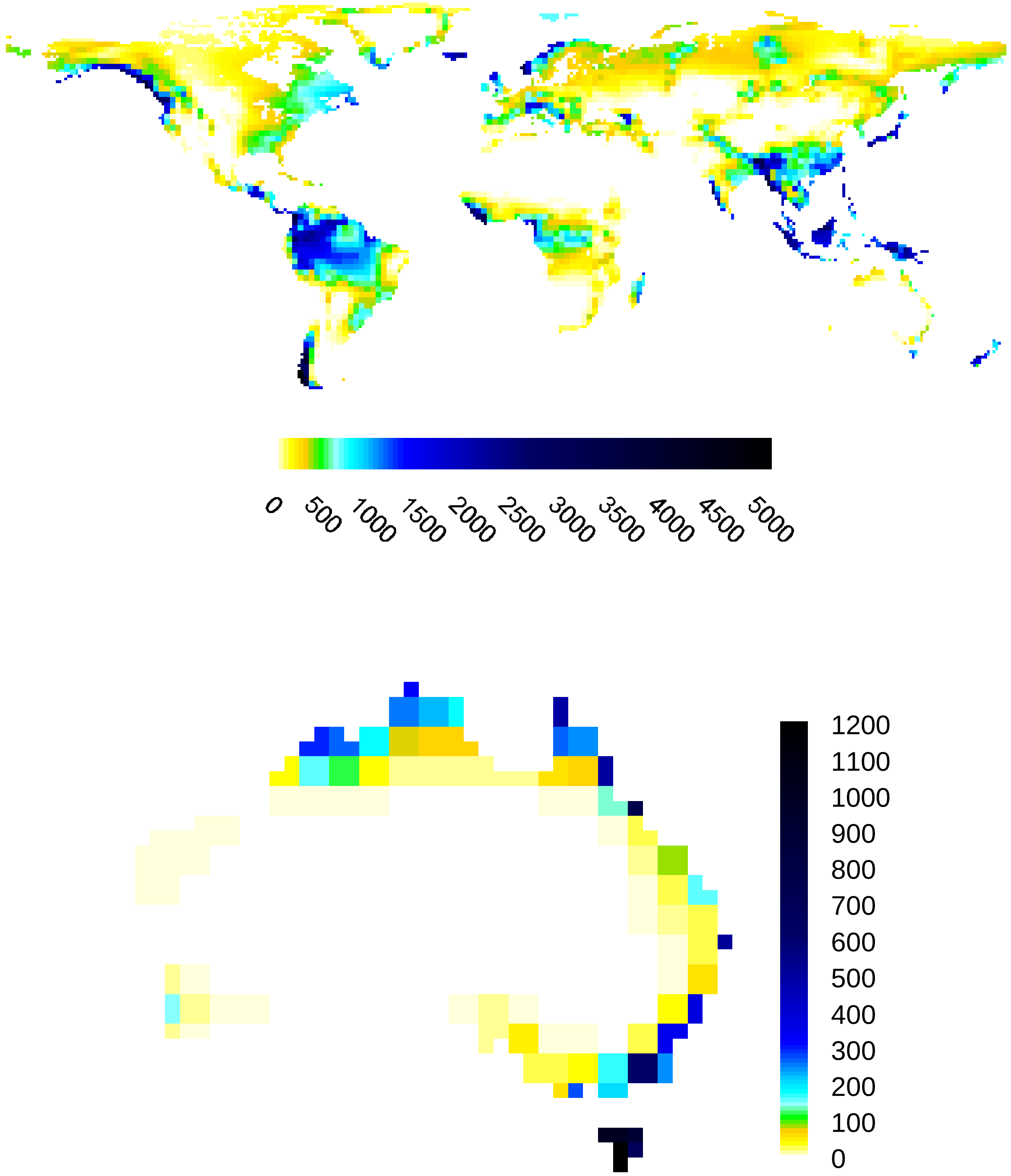

Figure 3: Global annual runoff gridded to 1 deg (Cogley 1994), with Australian data set enlarged (note expanded colour scale).

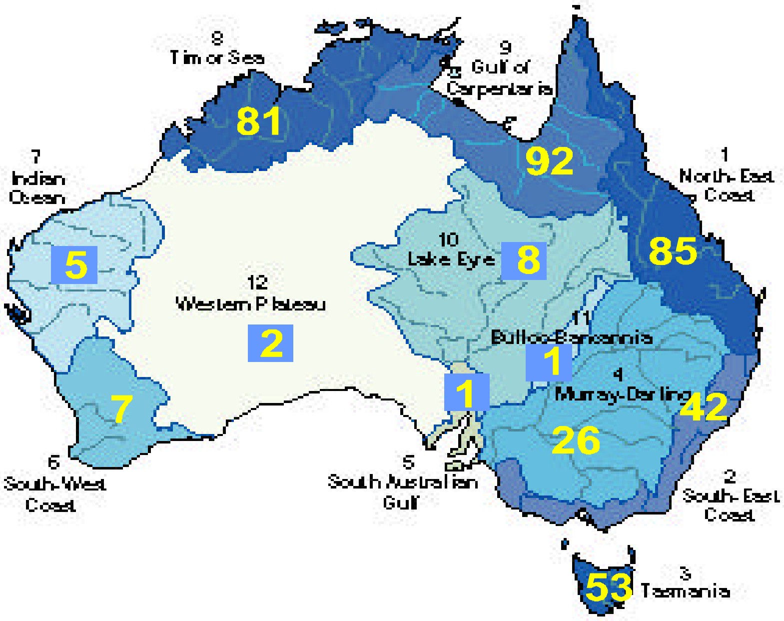

Figure 4: Annual mean runoff for major Australian drainage basins (AWRC 1985, SoE 1996 p. 7-4). Figures in yellow are annual mean runoff in teralitres (total 403 TL).

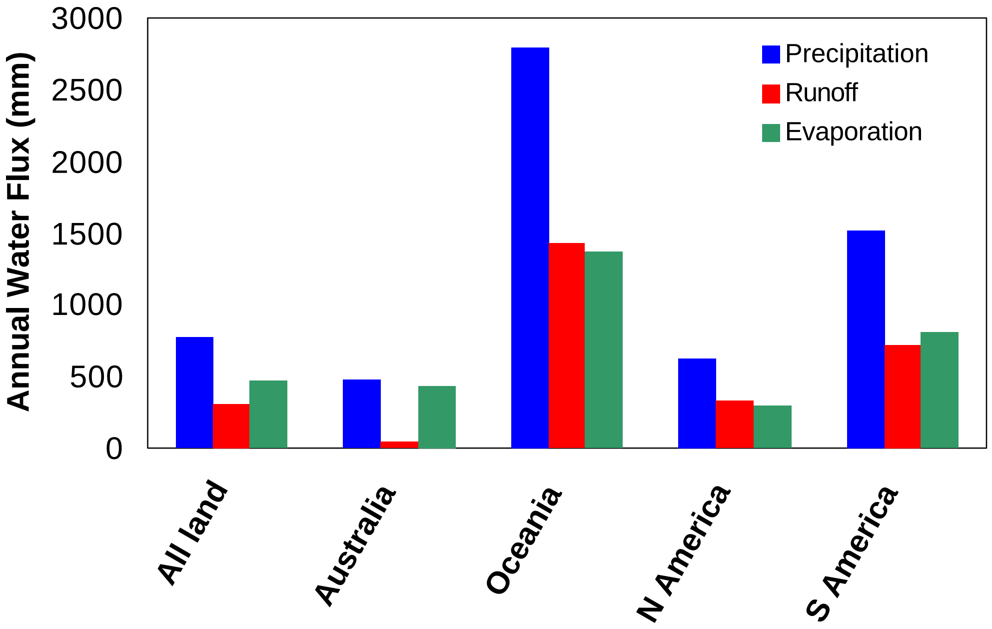

Figure 5: Comparison of the continental annual mean water balance for the Australian continent with the water balance for all land surfaces excluding Antarctica, and with the water balance for other continents.

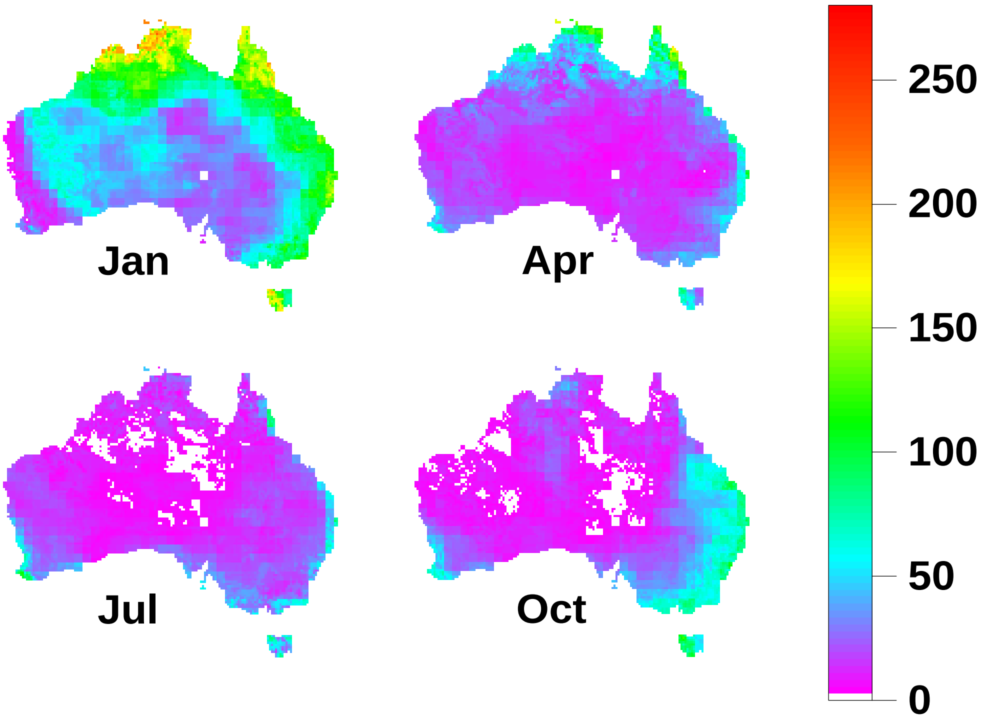

Figure 6: Modelled monthly averaged latent heat flux (W m^{-2}) for January, April, July, and October 1987 (Raupach *et al.* 1998).

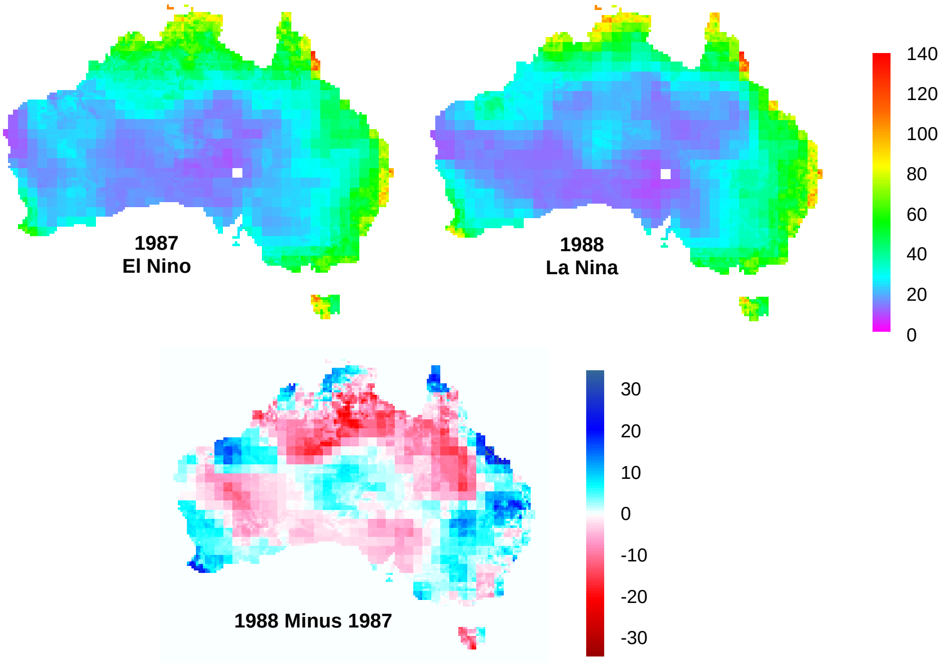

Figure 7: Comparison of modelled annual-average latent heat flux (Wm^{-2}) for 1987 and 1988, and the pattern of difference between the two years (Raupach *et al.* 1998).

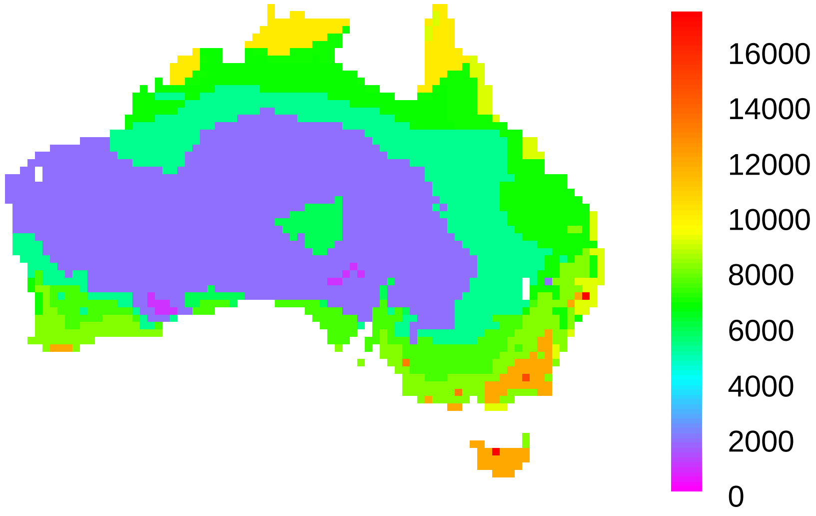

Figure 8: Soil organic carbon (g/m^2) for the Australian continent, from a 0.25 deg global data set (Woodward *et al.* 1995).

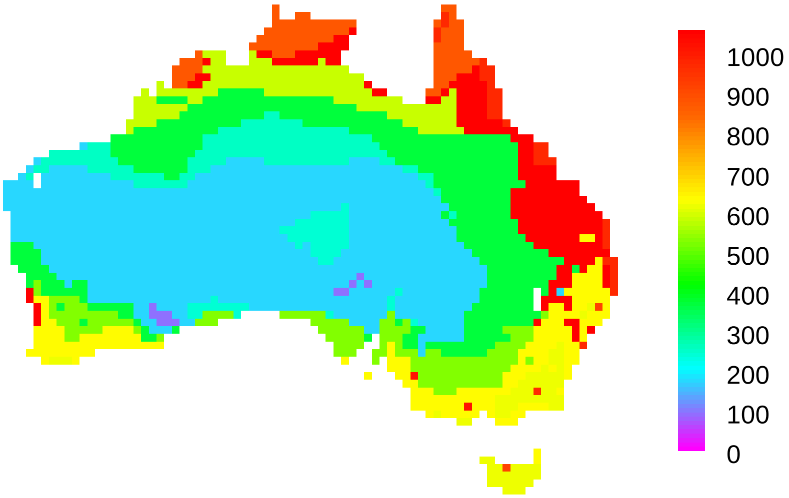

Figure 9: Soil nitrogen (g/m^2) for the Australian continent, from a 0.25 deg global data set (Woodward *et al.* 1995).