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To cite this version:

F. X. Dunin, C. J. Smith, O. T. Denmead. Hydrological change: reaping prosperity and pain in Australia. Hydrology and Earth System Sciences Discussions, 2007, 11 (1), pp.77-95. hal-00305596

HAL Id: hal-00305596

https://hal.science/hal-00305596v1

Submitted on 18 Jun 2008

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Hydrol. Earth Syst. Sci., 11(1), 77–95, 2007
www.hydrol-earth-syst-sci.net/11/77/2007
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Hydrology & Earth System Sciences

Hydrological change: reaping prosperity and pain in Australia

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Abstract

The adage: "*There is no such thing as a free lunch*", is relevant to land-use hydrology in Australia. Changes in land use to achieve greater productivity of food and fibre may have an adverse effect on the water balance and hence on the natural resource capital of a catchment. An altered regime of catchment outflow accompanies those land-use changes which, together with land degradation, impairs available water resources in quantity and quality and threatens enterprise sustainability, notwithstanding the initial improvement in productivity. Central to any hydrological change is an altered pattern of seasonal and annual water use by vegetation that has become modified in function with an amended transpiration fraction of daily evapotranspiration. In Australia, since measurement of evapotranspiration became feasible, the hydrological consequences of changes in land use have been determined, allowing the benefits in terms of plant productivity achieved through enhanced water use efficiency to be weighed against changed catchment outflows, diminished in either quantity or quality. Four case studies are presented as examples of ecological and hydrological changes: two deal with the upland forest environment and two with arable lowlands. In an upland eucalypt forest, following wildfire with subsequent regeneration from natural seedling establishment, substantial reduction in water yield occurred throughout a 50-year period of succession in the even-aged stand. In comparison, the effect of converting eucalypt forest to pine plantations was less detrimental to the yield of water from the catchments, with substantial growth increases over 30 years. In the lowlands, agricultural productivity, both as annual pasture and as crop, far exceeds that of natural perennial grassland and woodland. This increase in productivity comes not so much from any change to the yield of total water outflow but at the expense of water quality, compromised with increased material transport in suspension and solution resulting from accelerated erosion in association with outbreaks of soil salinity and acidity. The present study is aimed at optimising management to give plant production outcomes that ensure environmental protection through resource conservation. In the uplands, harvesting of water is the dominant consideration so that conservative management with limited plant productivity is sought. In the lowlands, the objective is to devise novel ecosystems with profitable plant production that exercises due control on outflow in maintaining the chemical and physical integrity of the edaphic environment..

Keywords: catchment area research

Introduction

Altering the balance of catchment outputs from water to food and fibre disturbs the ecological balance by influencing the rate of carbon turnover. Hydrological changes associated with this ecological disturbance then follow. Interventions, deliberate or inadvertent, prolonged or episodic, can modify the annual pattern of soil water dynamics. Interaction of this modified pattern with processes responsible for the gain, loss and transfer of soil water may alter outflow to provide tangible evidence for the response of a catchment undergoing change. Total outflow from a catchment comprises three constituent flows, overland flow, interflow or shallow lateral flows (short residence time with a half life of <6 months) and deep vertical drainage to recharge groundwater aquifers (generally long residence times with a half life of >5 years). The change can be expressed in terms of total outflow, in the proportions of the constituent fluxes, or in the water quality of these fluxes.

This view from an Australian watershed focuses on landscape elements considered, 30 years ago, to be in transition. Upland reaches under forest cover are contrasted with lowland areas under arable management with agricultural production. In these changes, the generality of original observations has been explored using the understanding gleaned from process studies, especially those involving direct measurement of catchment water use that comprise evaporation loss through interception and evapotranspiration (with components of direct evaporation from soil and of transpiration involving root water uptake).

The manipulation and conversion of vegetation changes

the evapotranspiration. This direct cause-and-effect makes understanding evapotranspiration central to understanding hydrological change.

In a review of Australian catchment research, Boughton (1970) asserted that the increase in infiltration accompanying observed reductions in runoff resulted from the development of greater soil water deficits in surface soils; this condition had been induced by enhanced uptake of soil water that accompanies vigorous growth. Experimental confirmation of this claim was obtained through a process study on paired catchments that demonstrated that productivity gains from increased pasture growth reduced runoff through increased evapotranspiration without any change in the infiltration properties of sorptivity and hydraulic conductivity (Dunin, 1976). Ongoing study into evapotranspiration has sought a robust characterisation of water use that enables diversity in plant function and morphology to be expressed as variability in the annual pattern of water use. A ceiling daily evaporation rate is deemed to be an important distinguishing feature of ecosystems and is defined for each of the three component processes of water use, interception loss from vegetation (E_I), direct evaporation from the soil surface (E_S) and transpiration by vegetation (E_U).

In the early 1960s, when McCulloch was applying an education in "natural philosophy" to advance scientific rigour in land use hydrology in equatorial East Africa, similar developments to address issues of land and water conservation were occurring in temperate Australia. Primary industry dominated Australian GNP and technological advances had lifted agricultural productivity and gross margins several-fold. Yet there was a price to pay in restoring land that had been scarred by erosion and also in combating emerging problems of solute mobilisation that were implicated in outbreaks of soil salinity and acidity. These forms of degradation cost the community dear in the impairment of the water resource through material transport in suspension and solution.

Conservation to tackle these issues had been in reclamation mode until the concept of the soil–plant–atmosphere continuum was articulated by Philip (1957) and incorporated in a strategy of land management to achieve ecological stability through changes in the water balance proposed by Downes (1958, 1959). Downes argued that productive outcomes were possible with an optimal water balance that maintained the chemical and physical integrity of the soil by exercising control on the rate of ouflow discharge. A novel ecology to meet these aims must be predicated on annual patterns of water use to achieve optimal soil water extraction to regulate outflow within certain bounds, while enabling critical uptake for desired growth levels. Field data on rates of evapotranspiration are crucial to the development of such novel ecosystems. McCulloch's recognition of such a need to support forest hydrology was evidenced by his establishment of a long-term micrometeorological study of pine evapotranspiration at Thetford (see Stewart and Thom, 1973; Gash and Stewart, 1977; Stewart, 1988). It is ironic that Australia, with a renowned reputation in micrometeorology, had lagged in applying that discipline in the service of water resource management. Collaboration within Australia has now provided detailed water use and growth data across grassland, forest and agriculture. This information will be used to provide a background parametisation to approach the four case studies of perturbed ecology analysed here.

Forest communities occupy much of the upland reaches of the Great Australian Divide that separates coastal rivers in south-east Australia from the extensive inland system of the Murray-Darling Basin with vast areas of arable lowland. The forests are dominated by numerous species of the hardwood genus, Eucalyptus. These forests have been subject to selective logging, clear felling and fire (both prescribed and accidental). This investigation of the hydrological consequences of changes in land use presents two case studies of upland forest disturbance: regeneration of eucalypts following the severe wildfire of 1939 and clear felling of eucalypts for pine plantations. Similarly, two agricultural case studies are presented, where fertiliser inputs have contributed to ecological change in grassland in one case and to improved crop agronomy in the other. Contrasting growth responses in each case are associated with unexpected change to outflow and challenge the axiom that increased growth demands greater water use. Their selection is made because a counter-intuitive hydrological response in both cases has demanded resolution using the background understanding gained from previous process studies. Again, the parameter set is invoked to resolve the respective paradoxes.

Theoretical considerations linking land use to hydrology

HYDROLOGICAL PERSPECTIVES

This overview contrasts two landscape units that differ in topography and general function in the use of the basic resources of light, water and carbon for plant growth. In the pristine state, resident plant communities have adapted to the environment for a steady state condition termed hydrological equilibrium (Eagleson, 1982). The rate of plant functioning is synchronised with climatic inputs of water and energy and interacts with soil conditions to develop an outflow regime that poses little or no hazard to the

persistence of the ecosystem. Characteristic flow patterns will evolve in different parts of the landscape and hydrological responses to perturbation can be expected to differ across the landscape.

Evergreen forest will be the climax vegetation when annual rainfall is high relative to energy inputs and there is adequate soil water supply for plant function throughout the year. Forests on the sloping terrain of the uplands of south-east Australia receive high rainfall due to orographic uplift of oncoming air, while lower temperatures at higher altitudes reduce the atmospheric demand for water. Hence, the forest ecosystem can be sustained even on the relatively shallow soils (< 2 m deep) such as those often encountered along the Australian Divide. This combination of factors results in periods of soil water excess that translate into perennial streamflow, making the forest environment the dominant contributor to riverflow in temperate Australia. The mechanics of flow are distinctive and offer benefits for urban water supply.

On forested hillslopes, rainfall infiltrates freely (Dunin *et al*., 1983) into a medium rendered highly permeable by tree roots (Talsma and Hallam, 1979). A conservative rate of soil water uptake by forests (McNaughton and Jarvis, 1983) pre-disposes redistribution of moderate proportions of infiltrated water to recharge to shallow aquifers which service streamflow with quickflow (Hewlett and Hibbert, 1969); this rapid transmission of shallow groundwater in a conduit network scoured out over a historical sequence of events results from pressure build-up from soil water excess in the rooting zone. A by-product of this rapid turnover of water is a leaching fraction which maintains solute concentrations at a low level in streamflow — a basis for good quality water.

The Murray-Darling Basin is characterised by arable agriculture on terrain with undulating to flat relief. Over much of the riverine farmland annual rainfall is low (< 650 mm), with a Mediterranean climate having abundant soil water in winter and spring. The natural ecosystems are dominated by perennial species, both grassy and woody (Moore, 1970). Woodland communities comprise evergreen overstorey species, such as acacias and eucalypts, widely spaced to enable sufficient light penetration to support an understorey of grasses and forbs. In some regions, woodlands give way to natural grassland dominated by a summer active perennial grass species, *Themeda australis*. The C_4 pathway metabolism of this species demands tissue temperature in excess of 15ºC before photosynthesis can proceed (Hatch *et al*., 1967) and so there is limited growth in winter and spring even when soil water is abundant. This community with winter dormancy will be compared with agricultural plant communities as an example of converted ecology forcing hydrological change.

In this semi-arid region, soils tend to be clay-based; the bulk density increases with depth and the hydraulic conductivity is low. Consequently, rainfall infiltration is confined largely to the rooting zone of the grassland. Overland flow is the major form of outflow, assisted in winter by the dormancy of the *Themeda* grass. Flow beyond the rooting zone, although irregular and infrequent, serves as an effective leaching fraction to recharge groundwater systems. With increasing aridity these outflow changes to surface-based flow is comparable to the Northern Hemisphere (Freeze, 1972).

Catchment outflow from natural grassland differs from that from forest because it originates as overland flow and it yields only some 5% of annual rainfall (Dunin, 1965). In contrast, forest with 1500 mm annual rainfall yields some 30% — exceeding the lowland value by more than an order of magnitude (Langford *et al*., 1980). Although the areal extent of the arable sector exceeds that of catchment forests by a factor of 2–3, its contribution to river flow is meagre. However, a lack of yield should not be mistaken for an absence of pollution hazard and the potential to impair water quality.

CHARACTERISING WATER USE BY PLANT COMMUNITIES

As a starting point to linking carbon and water fluxes, the rate of total water use (E_T) is defined as a series of evaporative processes (E_X) comprising interception loss (E_I) and the collective losses from soil ($E_{U/S}$) when the canopy is dry; these comprise losses due to direct evaporation from soil (E_S) and that from root water uptake for transpiration through the leaves in the canopy (E_U). Each of these processes is served by a water source W_X and each has a specific capacity $W_{I(C)}$, $W_{S(C)}$ and $W_{U(C)} \equiv W_{U/S(C)}$.

$$E_T = \alpha E_S + (1-\alpha) E_I + (1-\alpha) E_U \qquad (1)$$

when $W_I > 0$, $E_I > E_U = 0$, and for $W_I = 0$, $E_U > E_I = 0$. The partitioning coefficient, α represents that fraction of area contributing to E_T as direct evaporation from soil, while $(1-\alpha)$ is the area with contributions from vegetation either wetted with intercepted rainfall or unwetted and subject to stomatal control of transpiration; α depends on leaf area index (LAI) and was devised to represent the proportion of E_T occurring as E_S (Denmead, 1998). The form of the relationship is equivalent to a partitioning of the available radiant energy between two sinks or stores that deliver water vapour to the atmosphere. This distribution of heat energy between sources involves k, an empirical absorption

coefficient. The proportion of available radiant energy that impinges on soil, α, serves as a surrogate for the virtual area with direct evaporation from soil, while $(1-\alpha)$ represents the projected green canopy area achieving absorption of >90% of available radiant energy to drive transpiration.

$$\alpha = e^{-k\,LAI} \tag{1a}$$

The rate of water vapour flow to the atmosphere (Eqn. 2) is the lesser of two fluxes, the atmospheric demand, E_0, and the capability of the given store to supply water vapour, E_X, under the conditions prevailing. E_0 has been a central issue in debate about atmospheric demand and the impact of demand on evaporative response (Denmead and Shaw, 1964, versus Ritchie, 1981). The FAO formulation of reference crop evapotranspiration (Allen *et al.,* 1998) is useful in irrigation applications but, despite misgivings about an alternative solution for E_0, the Priestley-Taylor formula, E_{P-T}, has been selected here for its flexibility in dealing with seasonal variability in growth and energy supply in rainfed conditions.

$$E_X = \min(E_0, E_X) \tag{2}$$

Capability is indicated as an evaporation response, E_X, to available water in a given store at time t, $W_{X(t)}$, in the schematic diagram, Fig. 1, with a distinctive form for each process to describe sequences of daily evaporation. To deal with temporal variability in energy inputs and with spatial variability in soil hydraulic properties, the respective responses are shown in normalised form using variables, E_X/E_{P-T}, and $W_{X(t)}/W_{X(C)} = \theta_{X(t)}$.

The ramp form to describe transpiration response, E_U, calls for a two-stage specification with a ceiling level to account for energy limitation and a falling stage when $W_{U(t)}/W_{U(C)} < \theta_{U(\omega)}$ reflects soil water limitation once a state of incipient soil water stress, ω, has been reached. A constant value of $\theta_{U(\omega)}$ across a range of E_{P-T} has been adopted in producing a unique response of the normalised transpiration relationship in accord with the analysis of Tuzet *et al.* (2003) that confirmed the daily response proposed by Ritchie (1981). The ceiling rate, designated as $\hat{U}_U$, represents the average value of E_U/E_{P-T} for the plateau sector when $1 > W_{U(t)}/W_{U(C)} > \theta_{U(\omega)}$. Invariance of E_U/E_{P-T} across this sector, although debated, has been assumed here on the basis that opposing effects apply during an initial rise in stomatal resistance; increases in canopy temperature in response to increased resistance introduce an elevated gradient in vapour pressure which results in an unperturbed transpiration rate. For $W_{U(t)}/W_{U(C)} < \theta_{U(\omega)}$,

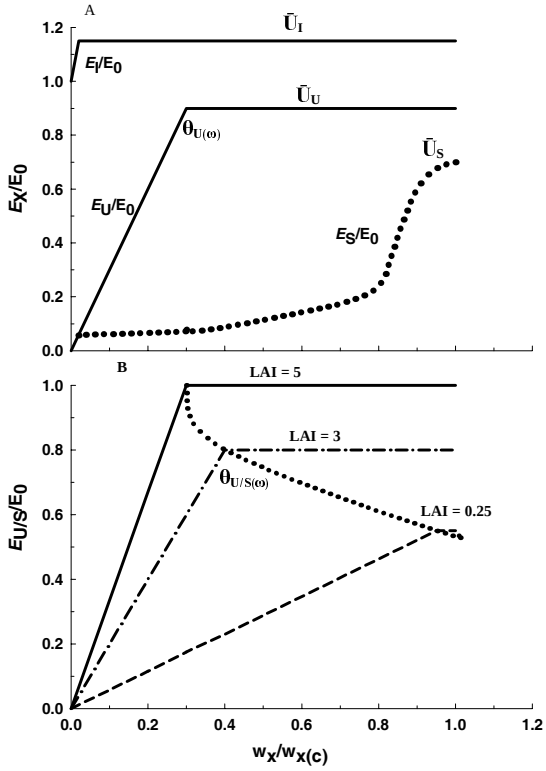

Fig. 1. *A. Schematic diagram of evaporation response to changing soil water in root zone indicating different progressions for the normalized daily rate, E_X/E_{P-T} in each of the constituent fluxes, E_I, E_U and E_S as well as in their respective upper limits $\hat{U}_I$, $\hat{U}_U$ and $\hat{U}_S$. B. Normalised response of evapotranspiration, $E_{U/S}/E_{P-T}$ to soil water changes by complex plant communities with canopies subject to variable area (LAI) either in space or time. The locus of points connecting the points of inflection for each response describes co-variation in $\hat{U}_{U/S}$ and $\theta_{U/S(\omega)}$ with changing LAI.*

$$E_U/E_{P-T} = \hat{U}_U\ ((\theta_{U(\omega)} - (W_{U(t)}/W_{U(C)}))/\ \theta_{U(\omega)})$$

describes the progressive reduction in transpiration as soil water reserves diminish. E_S response tends to be sigmoid, requiring specification for $\hat{U}_S$ and $W_{S(C)}$. This functional form, $E_{S(t)} = f(W_{S(t)})$, is based on the power law relationship for steady state gain and loss of soil water (Philip, 1957, 1967),

$$\Sigma E_S = E_{P-T}\ \hat{U}_S\ t^{1/2},$$

where $\hat{U}_S = E_{S(1)}$ is the maximum daily rate of soil evaporation from a store, full to capacity, $W_{S(C)}$ on day 1 after replenishment. The derivative of this relationship yields $E_{S(t)}$ to be matched to the corresponding water status of the store determined as

$$W_{S(t)} = W_{S(C)} - \hat{U}_S\,(t-1)^{1/2}.$$

$W_{S(C)}$ is the water available to the plant in surface soil ~25 cm

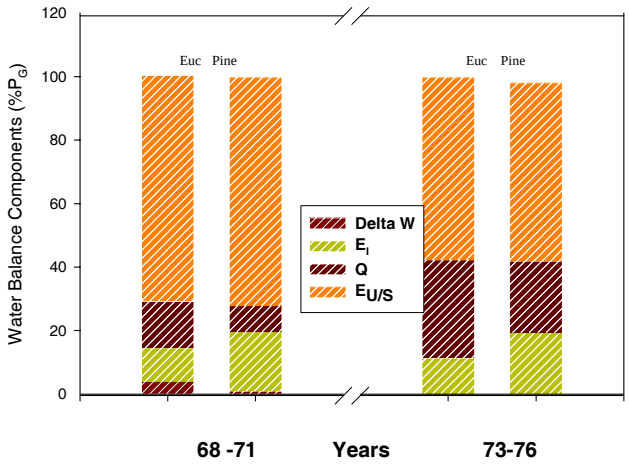

Fig. 2. *Water balance comparison of eucalypt woodland with pine plantation at Lidsdale, N.S.W., with the two sets of paired catchments and with the individual components represented as a percentage of catchment rainfall.*

deep for direct evaporation and is generally < $W_{U(C)}$. In Fig. 2a, 0.7 = $\hat{U}_S < \hat{U}_U < \hat{U}_I >$ 1.0 applies; this distinguishes the upper bound for each form of evaporative loss. Values of U_S generally fall within the range 0.3–0.7 depending on the hydraulic properties of the upper soil horizon and can be rated on the basis of textural category.

Interception loss, E_I, is characterised by enhanced rates with $\hat{U}_I$ >1.0, shown as a step function with an enhanced but constant rate at $\hat{U}_I$ = 1.15 while 0< $W_{I(t)}$ < $W_{I(C)}$. At $W_{I(t)}$ =0, $\hat{U}_I = \hat{U}_U$, for transpiration to be re-initiated after adjustment to $W_{U(t-1)}$ for infiltration gain from net rainfall input, $P_N = P_G - E_I$. Aerodynamic roughness is the major determinant of enhancement to increases in E_I/E_0 with $\hat{U}_I$> 1.0, the value of which is a function of canopy height. In the schematic diagram, the level of enhancement at 15% greater than E_{P-T} is typical of an agricultural crop < 1 m tall, while $W_{I(C)}$ ranges between 0–2 mm. Agricultural plant communities with moderately turbulent regimes experience interception loss during sunlight from the interception store alone, indicating that interception losses during rainfall are absent or negligible. Generally, the daily quantity of interception loss is equal to or less than $W_{I(C)}$.

Forest trees, commonly >10m, generate a highly turbulent atmospheric boundary layer with large eddies. This greater turbulence induces high $\hat{U}_I$ that results from variable E_I/E_0 as1< E_I/E_0<5 while W_I>0. Variable enhancement of E_I has been attributed to $E_I/E_0 = f(W_I/W_{I(C)})$ (Rutter *et al.,* 1972). These features enhance the interception loss rates compared to short agricultural plant communities with detectable vapour fluxes during rainfall (Rutter,1967). The combination of a phase of interception depletion post-rainfall and one of continuing loss during rainfall has been described as a linear function of rainfall for the progress of cumulative interception loss during a rain event (Gash, 1979). The slope of this relationship, Ω, can be robust across time scales for a given community such that an event-based value can be applied at the annual scale (Dunin *et al.,* 1989) to simplify estimation of interception loss by forest and woodland communities.

The hydrological significance of the interception process may be gauged using the concept of additional vapour loss consequent on the imposition of an interception store (Rutter, 1968). Assuming complete infiltration of net rainfall P_N, soil water gain (W_P)

$$W_P = P_N = P_G - E_I$$

is compared with a notional gain ($\hat{W}_P$) that assumes complete infiltration of gross rainfall, P_G, to be depleted only by transpiration operating at $U_{U/S}$ for that post-rainfall period (δτ) with a wetted canopy,

$$\hat{W}_P = P_G - (E_{0*}\ \hat{U}_{U/S\ *}\ \delta\tau).$$

An estimate of this incremental loss due to interception ($\Delta W_I = W_P - \hat{W}_P$) can be derived from known E_I and the respective ceiling rates of interception loss, $\hat{U}_I$, and that as evapotranspiration for a dry canopy, $\hat{U}_{U/S}$.

$$\Delta W_I = E_I\,(\hat{U}_I - \hat{U}_{U/S}) \qquad (3)$$

In the absence of measurements of E_I, estimates can be made using a distinction for forest and agricultural communities for a specified study interval, such as a season or a year with measured daily rainfall.

For forest, with a designated value of Ω as the interception coefficient for the given forest type,

$$E_I = \Omega_* \Sigma P_{G(n)} \qquad (3a)$$

where ΣP_G is the accumulated value of daily gross rainfall for the specified interval with n wet days. For an agricultural community with an interception capacity, $W_{I(C)}$, and a study interval with x wet days where $P_G > W_{I(C)}$ and an accumulated gross rainfall for those (n-x) wet days with $P_G < W_{I(C)}$ designated as $\Sigma P'_G$,

$$E_I = (x_*\ W_{I(C)}) + \Sigma P'_{G\ (n-x)} \qquad (3b)$$

Anticipating results, values have been assigned to the terms of Eqn. 3 to assess the role of interception in water balance issues of land use. For an agricultural crop of wheat,

E_I = 50 mm has been assumed for seasonal interception (Leuning *et al.,* 1994), $\hat{U}_I$ = 1.15 (Dunin *et al*., 1978) and $\hat{U}_{U/S}$ = 1.0 (Dunin *et al.,* 1999) to deduce that an increment of 7.5 mm of seasonal E_T is denied to those soil water loss processes implicated in partitioning between water use and outflow. An explicit account for interception in agricultural communities hardly seems warranted. By contrast, the case for an account of forest interception loss is substantiated on the basis of a ΔW_I calculation of 105 mm in 1000 mm annual rainfall of which 150 mm is represented as interception loss (Dunin *et al.,* 1988) and values of j_I = 1.50 and $\hat{U}_{U/S}$ = 0.8 are deemed appropriate based on this reference and Rutter (1967). A lack of due account of 105 mm would mean that annual infiltration is overestimated to be expressed as a doubling in computed streamflow (Q) from a forest catchment with observed $Q \equiv 0.1\ P_G$.

The forest environment is complex, with botanical diversity and a layered structure with distinctive storeys; three are common for eucalypt forest. Partitioning $E_{U/S}$ through Eqn.(1a) is inappropriate as α is defined to deal with two different sinks of heat from available radiant energy: namely, soil and green vegetation. The range of heat sinks and their relationship to water sources within the forest canopy demand an elaborate specification for the disposition of energy which complicates analysis in the absence of measured fluxes for the individual processes. Instead, characterisation for E_I and $E_{U/S}$ alone can lead to reproducible results once the role of leaf area index (LAI) is defined to account for variation in $\hat{U}_{U/S}$ and $\theta_{U/S(\omega)}$. Co-variation of $\hat{U}_{U/S}$ and $\theta_{U/S(\omega)}$ with changing forest LAI is described in terms of co-ordinates along the locus of points connecting $\theta_{U(\omega)}$ across the family of ramp functions, each designated with a specific LAI (Fig. 1b). These different functions, each conforming to *The Law of Limiting Factors,* are based on measured daily values across a range of eucalypt communities, each possessing a characteristic LAI that tends to be stable over a series of years unless catastrophic conditions prune the canopy (Dunin, 2002). This empirical characterisation is justified for a general description on the grounds that, over much of the LAI range, E_U is the dominant determinant of the combined flux to account for a coherent progression in $\hat{U}_{U/S}$. The failure of E_S to complement E_U in attaining $\hat{U}_{U/S}$ =1.0 at moderate to low values of E_0 (unlike crops) can be attributed to significant mulch effects of litter on the soil surface in forest and woodland. A similar description is applicable for natural grassland where the summer growing season is typified by dynamics in green LAI, while still maintaining a substantial component of senescent standing biomass.

CARBON/WATER LINKAGES

Biological response, as growth rate M (g DM (standing biomass) m^{-2} d), can be described in terms of transpiration rate, E_U, (mm $d^{-1} \equiv kgH_2O\ m^{-2}d$) and its efficiency, TE (gDM/kg H_2O).

$$M = E_U * TE \tag{4}$$

$$TE = (ITE/D) * (RUE/J) \tag{4a}$$

where ITE is the intrinsic transpiration efficiency for carbon dioxide assimilation (A), an entity that involves scaling the assimilation ratio, A/E_U, with the atmospheric humidity deficit, D, to provide a nearly constant value during active growth; this applies across species with a common metabolic pathway (C_4 or C_3) while temperature conditions are optimal (T_{OPT}) for the rate of conversion of assimilated CO_2 to hexose (Rawson *et al.,* 1977; Sadras *et al.,* 1991). A value of ~12 g CO_2/ (kg H_20/kPa D) applies for C_3 species and a doubled value seems appropriate for C_4 pathway species. Radiation use efficiency (RUE) is expressed as dry matter of standing biomass per unit of intercepted solar radiation. J, the assimilate energy quotient, refers to the mass of CO_2 assimilated per unit of intercepted solar radiation. Both these energy-based descriptors have units of mass/energy intercepted by green biomass and imply unconstrained assimilation of CO_2 and, hence, an absence of soil water stress. J is applied here with a value of 3.47g CO_2/MJ intercepted solar radiation, derived on the basis of an energy requirement for CO_2 fixation (11.5 MJ/kg CO_2) and the active radiation component for photosynthesis is represented as 4% of total solar radiation (slope of light response curves). RUE is the distinctive characteristic to define growth response for a plant species or community and other information involves time-averaged values for air temperature and humidity. Air temperature is needed to determine if the optimum range for metabolism applies in the study time interval; outside this optimal temperature window, some fractional value of ITE must be invoked. Temperature and absolute humidity of air at some reference height are required for solutions of D.

DISTINGUISHING LAND USE FOR RESOURCE USE

A set of characteristic features for each of three forms of land use has been derived from a detailed study of water use, growth and carbon assimilation in the respective plant communities (Table 1). Each set, comprising a common array of 11 entities, represents a summary of the foregoing theory in dealing with plant function through the interactive resource use of water and carbon; a further six entities are

Table 1. Variation in critical features pertaining to variables of water use (WU) and transpiration efficiency TE across different forms of land use of regenerating natural forest (RF) natural grassland (NG) and cropping rotations with wheat (CR). Values presented are drawn from nominated literature except those in italics where estimates are made using principles outlined in those three references cited under *11* and *12*. The other unsupported information for T_{OPT} is drawn from ecological and agronomic observation and D the average growing season vapour pressure deficit of the atmosphere is taken from local weather observation.

Resource	*E/M*	*Entity*	*Units*	*RF*	*NG*	*CR*	*Sources*
Water	E_I	$W_{I(C)}$	mm	0.51	2.02	0-23	[1]Dunin et al., (1988), [2]Aston (1979), [3]Leuning
E_X		$\hat{U}_I$		1.54	1.155	1.153	*et al.*, (1994), [4]Rutter (1967), [5]Dunin and
Eqn.(1)		Ω	%	151	n/a	n/a	Reyenga (1978), [6]Dunin *et al.*,(2001),
(mm d^{-1})	E_S	$W_{S(C)}$	mm			326	[7]Denmead *et al.*, (1996) [8]Tuzet *et al.*, (2003),
		$\hat{U}_S$				0.76	[9]Dunin *et al.*, (1984), [10]Aston and Dunin
		k				0.617	(1980)
	E_U	$W_{U(C)}$	mm			1106	
		$\hat{U}_U$				0.98	
		$\theta_{U(\omega)}$	$m^3\ m^{-3}$			0.78	
	$E_{U/S}$	$W_{U/S(C)}$	mm	2109	1405	1106	
		$\hat{U}_{U/S}$		0.89	0.810	1.09	
		$\theta_{U/S(\omega)}$	$m^3\ m^{-3}$	0.79	0.710	0.79	
		LAI	$m^3\ m^{-3}$	3.09	0–25	0–46	
Biomass	TE	ITE	kPag kg^{-1}	1211	2511	1211	[11]Tanner and Sinclair (1984),
M		RUE	g MJ	0.6	0.8	1.412	[12]Whitfield and Smith (1989),
Eqn.(4)		TOPT	°C	*25*	*30*	*15*	[12]Sinclair and Muchow (1999)
(kg $m^2\ yr^{-1}$)		D	kPa	1.2	1.6	0.8	

nominated for cropping rotations (CR) for which partitioning for E_U and E_S is possible. The interaction in resource use is expressed through LAI dynamics with control on water use for its rate and its composition for E_U that leads to determination of growth rate subject to environmental influences, through T_{OPT} in setting growth period and D in regulating TE. Growing season is the time interval that comprises daylight conditions with canopy temperature varying within an optimal temperature window that enables metabolism of assimilated CO_2 to hexose to proceed at a faster rate than respiratory requirements for maintenance. This condition is approximated simply as Ta = $T_{OPT} \pm 10$°C and these temperature conditions have been used to compile an average D for the growth period. Comparison across the data sets then offers insights into variation of critical features that will be encountered in the case studies given in Table 2.

A phase difference in the pattern of water use is notable in comparing natural forest (RF) and natural grassland (NG) with agricultural cropping rotations (CR) (Dunin *et al*., 1999; Smith *et al*., 2000). T_{OPT} accommodates seasonal differences by reflecting the timing of EE_U dominance in $E_{U/S}$. The early spring occurrence of peak $E_{U/S}$ in CR (Sept/Oct) is consistent with daytime average temperatures of 15°C along Latitude 35°S in southern Australia, while peak $E_{U/S}$ in Nov–Dec for the natural ecosystems, RF and NG, are reflected in the higher values for T_{OPT} of 25°C and 30°C for these respective communities. Growing season length and timing are implied in D for determining TE regulation. Summer season activity by NG is indicated with the highest D value of 1.6 kPa although this regulation is offset by a higher ITE typical of C4 plant communities. The intermediate D value of 1.2 kPa for RG indicates year-round growth potential by eucalypt communities, although summer bias and a sinusoidal $E_{U/S}$ progression coupled with that of solar radiation are consistent with prolonged growth. The lowest value of D as 0.8 kPa for CR denotes the temperate growing season for annual crops, May to November, with high TE that is instrumental in levels of seasonal growth of 10–15 t ha^{-1} of wheat biomass to be comparable with the annual growth of young eucalypt forest from an extended growth season with double the rainfall. This higher growth rate of wheat is attributable to its $\hat{U}_{U/S}$ value of 1.0 that is the maximum amplitude of all three of the annual patterns. The lowest amplitude occurs with NG whose $\hat{U}_{U/S}$ value of 0.8 can be limited in summer periods of infrequent rainfall to result in the lowest annual productivity of 2 t ha^{-1} (Groves, 1967). An intermediate capacity of plant available water, $W_{U/S(C)}$, in NG was insufficient to temper effects of rainfall deficiency on growth, notwithstanding high TE. By contrast, high growth rates of CR were not perturbed greatly by low

Table 2. Salient features involved in each case study indicating primary impact of intervention on hydrology with changed values (bold) together with values of associated unperturbed aspects. The outcome of retrospective analysis to maintain consistency between hydrological and ecologic change through Eqn. (4) is shown as variation in those critical features designated in italics. Units for each feature as shown in Table 1 are retained here unless specified as % of rainfall P (mm) with subscripts to indicate average annual over the study period (AAS), long term average annual (LTAA) and seasonal total for study crops (SEAS).

Case Study	*Outputs*			*Perturbed entities & relevant characteristics*						*Environmental conditions*		
	Q/P (%)	W	E /P (%)	Ω	T_{OPT}	RUE	$\hat{U}_{U/S}$	$\hat{U}_I$	$W_{I(C)}$	D	P_{AAS}	
Pine	8.3	0.9	71.9	**0.19**	***15***	0.75	0.8		0.8	1.2	870	
Euc	14.2	0.3	71.2	**0.12**	***25***	0.65	0.8		0.3	1.2		
				LAI	RUE	$\hat{U}_S$	$\hat{U}_{U/S}$				P_{LTAA}	
R Ash	37.5	1.5	*72.5*	**2.0**	0.5	0.7	*1.0*			1.0	1600	
M Ash	75.0	0.43	*20.6*	**3.5**	0.4	0.2	*0.4*			1.0		
				T_{OPT}	RUE	LAI	$\hat{U}_{U/S}$	W_I	ITE		P_{AAS}	
NG	5.0	2.2	0.94	**30**	0.9	0-2	1.0	75	25	1.5	520	
IP	0.5	6.3	0.96	**12.5**	0.85	0-3	0.7	50	12	0.7		
				LAI	E_U	$\hat{U}_{U/S}$	ITE	TE	RUE		P_{SEAS}	T_{OPT}
WC(N0)	22.3	1.52	83.9	**0-4**	145	0.8	12	7.0	1.34	0.66	417	15
WC(N+)	19.7	1.01	95.2	**0-3**	209	0.8	12	7.0	1.34	0.66		15

$W_{U/S(C)}$ in a seasonal regime of low E_0. RF with conservative $\hat{U}_{U/S}$ accompanied by high $W_{U/S(C)}$, has important properties for ecosystem stability under high rainfall through sustained but moderate growth. In such an environment, significant proportions of the rain are released regularly from the root zone to become perennial streamflow and creating a reliable water harvest.

These considerations allow differentiation of land use, in terms of a suite of critical features including biological rhythm and water use. The purpose of this approach is to gain understanding that will enable restoration of the resource base to a sustainable production level. The approach entails selection of a subset of salient features implicated in change and an assumption of their magnitude of change in each of the four case studies. This information is applied to deconvolute the rainfall/runoff process to articulate the critical flow pathways that contribute to total outflow from the ecosystem. The changed water use driving hydrological change is then assessed for its consistency with observed changes in plant productivity. Table 2 contains the information on water use and the other features subject to change in the specified case study. Also included are retrospective analyses based on consistency between changed production and water use achieved using Eqn. (4).

Case studies of hydrological change

FOREST MANAGEMENT

Forest management ranges from clear felling to a policy of minimal intervention designed expressly to protect water quality. Both case studies presented here deal with removal of mature forest: the first was a deliberate conversion of mature forest into pine plantations while in the second, wildfire destroyed a mature forest reserved exclusively for water supply. In the first case study, between 1950 and 1980, mature eucalypt forest with a history of selective logging was clear-felled and replaced with plantations of *Pinus radiata* to overcome a national shortfall in softwood for paper production. The second case study relates to the wildfire of Black Friday (Friday, January 13, 1939) which devastated the vegetation over a set of catchments which, since 1886, had been dedicated to the urban water supply for Melbourne and were excluded from timber production and general public access. This was the most significant event in the history of fire ecology of temperate Australia.

The first Australian study of hydrological response to change in forest species was in Lidsdale State Forest, 130 km WNW of Sydney at altitude 975 m (Smith *et al*., 1974). In replicated paired catchments, the water used by dry sclerophyll forest was compared, in separate study periods of between 2.5 to 3 years, with that of ~35-year old plantations of *Pinus radiata*. Each period was scaled to an annual average for each component of the water balance

Table 3. Water balance components, scaled for annual rate, mm yr^{-1}, from Lidsdale State Forest, to compare pine catchments with a eucalypt control catchment in two separate studies.

Period	17 Oct 1968–28 April 1971		1974–1976	
Catchment	Pine #2	Eucalypt #6	Pine #1	Eucalypt #6
Precipitation, P_G	871	895	842	870
Interception, E_I	163	95	183	99
Nett rainfall, P_N	708	800	659	771
Runoff, Q	72	127	190	269
Soil water change, ΔW	9	35	–3	1
Evapotranspiration, $E_{U/S}$	627	638	472	501

(Table 3) using data from the relevant experimental catchments at the Lidsdale site (Pilgrim *et al*., 1982). Contrast and consistency in the individual components are apparent, both between study periods and between plant communities, and this is emphasised with a representation of each component as a proportion of the catchment rainfall.

Variation in annual gross rainfall, P_G, was small between catchments and between study periods. Rainfall distribution must have differed between periods to cause Q_6 (eucalypt control catchment) to be doubled in the later period as was the case with pine catchments Q_1 and Q_2. There was less runoff from the pine catchments. The runoff difference between pine and eucalypt catchments was $Q_6 - Q_1$ = 55 mm while the later value was $Q_6 - Q_2$ = 79 mm; this constituted an overall difference (67 mm) as 7.7% of the time-averaged rainfall of the three catchments (870 mm). This value corresponded well with interception loss differences of –68 mm and –84 mm between catchments, an average value of 8.7% for proportionate interception loss between pines and eucalypts that may be deemed to be time invariant at the site. These results are qualitatively consistent with the greater stature of pines over the eucalypt stand (31 compared to 15 m); this increased aerodynamic roughness and enhanced evaporation during rain. At the same time, a 50% difference in basal area (12 to 19 m^2 ha^{-1}) increased interception capacity from estimates of 0.5 mm for the eucalypt to 0.8 mm for the pine. These determinations accord with a more recent generalisation for greater interception loss by pines over eucalypts at a given site, based on a review of Australian data (Feller, 1979). The magnitude of the difference may be stated as $0.10 < \Omega$ (EUC) < 0.25 and Ω (PINE) = Ω (EUC) + 0.10, assuming sufficient stature has been attained to ensure that a linear description as $E_I = f(P_G)$ applies.

Runoff reduction was accounted for solely as a result of increased interception by pines relative to eucalypts, given that evaporative losses by $E_{U/S}$, defined for conditions of a dry canopy, were comparable between communities (Smith *et al*., 1974). This claim was substantiated in the later period when measurements in catchments 2 and 6 implied that the additional water use by enhanced interception loss is associated with the greater biomass production of pines over eucalypts. Leuning *et al*., (1994) deduced that carbon gain can proceed in crops while $W_I > 0$ and that the productive component of water use nominated as E_U must incorporate interception losses. For forest, interception loss only during sunlight would qualify for inclusion in productive water use, so 30% of total E_I was incorporated because 30% of forest interception loss was observed to occur during daylight near Bateman's Bay, 200 km south-east of Lidsdale (Dunin *et al*., 1988). A value of 25 mm has been derived as the differential interception component to be incorporated as productive water use. Combined with a TE value of 2.1 g kg^{-1}(using D= 1.2 kPa and RUE = 0.75 from Table 2), a value of 0.05 kg m^{-2} yr^{-1} is derived to represent only 10% of the difference in growth rates between eucalypts and pines at Lidsdale as 0.3 and 0.9 kg.m^{-2} yr^{-1} respectively (Lambert, 1979). Clearly, comparing $E_{U/S}$ between forest communities is satisfactory for assessing hydrological controls on flow but it masks important differences for developing growth differences, presumed to be in the partitioning of $E_{U/S}$ as well as in seasonal differences for metabolic function which confers advantages in TE for pines over eucalypts.

Vast tracts of mature forest of *Eucalyptus regnans* were devastated in 1939 in Melbourne's water supply catchments (termed the Maroondah catchment group 60 km north-east of Melbourne) in 1939. There followed a regeneration phase with an even-aged juvenile stand raised from seed in the initial phase, development of which had been conditioned by fire for germination and by light for seedling growth. The species exists as a series of pure stands in niches of high soil water availability along the soil catenary sequence (kraznosem) between the watershed or divide and the catchment outlet; species abundance ranged between 15 to 50% of catchment vegetation across the set of five catchments, with annual rainfall between 1000 and 2000 mm. Post-1939, the juvenile regrowth varied from 24

to 88% cover as replacement for mature *E. regnans*. The rest of the catchment vegetation comprises a small proportion of rain forest vegetation, often as understorey, and a further two components of wet sclerophyll eucalypt forest. Although aspect has a role in the distribution of these eucalypt species, one of these components is *E.delegatensis*, a fire-sensitive species of lower stature than *E. regnans* but given the same common name of mountain ash. A mixed species component of fire resistant species occupies the drier end of the soil water spectrum and their abundance becomes dominant as catchment rainfall approaches 1000 mm. The recovery from the 1939 fire by the mixed species component has been almost complete due to vegetative propagation endowed by an epicormic storage organ, a common strategy among the numerous eucalypt species. *E. regnans* is renowned as the world's tallest hardwood, with mature stands commonly in the range 50–75 m tall, while individual species have heights >100 m. The attainment of such heights can introduce transmission resistance to sap flow and slow transpiration in mature stands, an aspect of plant/water relations to be considered later.

Evidence for a distinctive response of mountain ash forest to fire was provided by Langford (1976) with a statistical analysis and a model to describe streamflow reduction below the pre-1939 levels. This response was counter-intuitive based on generalisations for forest clearing with a phase of increased streamflow prior to stabilisation as re-vegetation progressed to restore the initial water balance (Bosch and Hewlett, 1982). Brown (1972) reported this type of hydrological response to fire for a mixed eucalypt community with a five-year phase to stability in a sub-alpine region at Yerongabilly along the Divide in south-east Australia. Langford devised a precise multiple-regression relationship for average depression in water yield (ΔQ- mm) over a period of 20 years (1944–1964), using as dependent variables the percentage of regrowth of *E. regnans* (SP_{REG}) and of the mixed species component(SP_{ME}).

$$\Delta Q = 153 + 1.79\ SP_{REG} - 2.29\ SP_{ME} \qquad (5)$$

Thus, water yield volume reductions as high as 30% can be associated directly with the regrowth of *E. regnans*; this suggests much higher consumptive use by the juvenile counterpart over the mature form. The term relating to mixed species cover was interpreted as a surrogate for catchment rainfall with a negative sign to reflect reduced sensitivity of hydrological response to regrowth as catchment rainfall became lower; that accords with increasing SP_{ME}. This insight has prompted a range of studies in stochastic hydrology and plant physiology, seeking to clarify the issue of declining urban water supply.

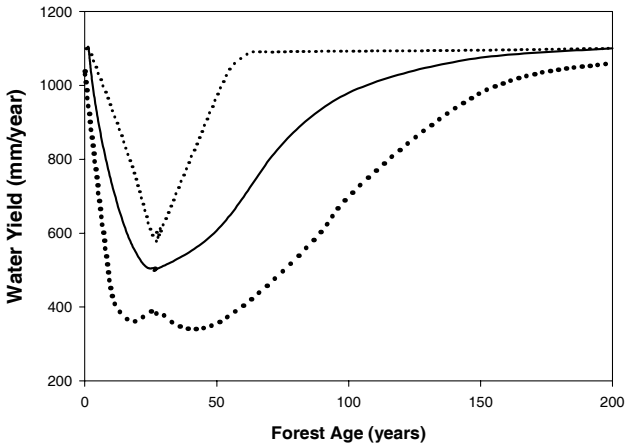

Fig. 3. *The generalised Kuczera curve describing water harvest decline (with 90% confidence limits), normalized for an average annual rainfall of 1600 mm, with forest age in catchments having 100% composition as mountain ash (After Watson* et al.,*1999).*

A development of Eqn. (5) has been devised with a statistical fitting procedure to the 40-year record of post-burn streamflow data from the Maroondah catchments to describe ecological succession in the ash forest with a time series of annual discharge (Kuczera, 1987). Two distinguishing features, the time to and the magnitude of minimum annual flow, are specific for a given catchment response determined largely by the amount of ash regrowth after the 1939 wildfire. Figure 3, designated as the generalised Kucerza curve, describes annual flow with age of regrowth, adjusted for variation around average annual rainfall, taken here to be 1600 mm, for a catchment composed solely of ash forest (Watson *et al.,* 1999). This has a response time of 27 years for an approximate 50% reduction in yield which equates to 600 mm as the maximum change in water use between active regrowth and mature forest. Kucerza cautioned the accuracy of statistical description for the recovery phase of streamflow during succession towards maturity, indicated as being after 2040. This phase is clearly critical for operational management of forest and prompted the deterministic approach of Watson *et al.* (1999) to describe the annual series of streamflow yield for the post-fire succession. This approach was predicated on the dynamics of LAI for a forest age sequence spanning a century to account for the effective control on evapotranspiration processes. This surrogate approach to stomatal function during forest succession has been facilitated by a coherent relationship between cross-sectional area of sapwood and canopy LAI. However, for ash forest progressing towards maturity, the trend for increasing cross-sectional area is interrupted with reductions in sapwood area, partly due to tree thinning but also apparent on an individual tree basis (Dunn and Connor, 1993; Jayasuriya *et al.,* 1993).

At this stage of reducing sapwood, departure from a unique response in the sapwood area/LAI relationship is apparent with a retreat from a constant ratio to a falling value with time of sapwood area/LAI (Watson *et al.,* 1999). This decline suggests a change in stomatal function for greater control that extends beyond the scope of the influence of falling LAI to conserve soil water. A similar argument has been mounted from Karuah, New South Wales, where a phase of pronounced streamflow reduction has occurred in the aftermath of forest clearing of experimental forested catchments with average rainfall ranging between 1475 and 1750 mm (Cornish and Vertessy, 2001). These communities are dominated by *E. saligna* and *E. laevopinea*; the rapid water use in the regrowth phase resembles *E. regnans* with a phase of reduced streamflow in the early stages of forest succession. Direct evidence for an approximate threefold difference in E_U between mature and juvenile stands of *E. sieberi* (Roberts *et al.,* 2000) adds weight to the claim that profligacy in resource use during regrowth may well be a general feature of a range of eucalypt communities.

An independent approach to evaluating the changing rate of water use during succession involves an inverse solution of Eqn. (4) based on the rate of regrowth reported for different stages of succession after burning (Brooks and Turner, 1964; Langford, 1976). For a 25-year old ash stand at pole stage, a height increase of 1.25 m y^{-1} can be rated as the equivalent of 1.5 kg m^{-2} y^{-1} for the rate of dry matter accumulation in above-ground biomass (Attiwill, 1979). This growth is assumed to result from continuous functioning of the canopy over an annual period subject to average vapour pressure deficit (VPD) of 1.0 kPa. An average canopy leaf area of LAI = 3.5 is applied at the pole stage (Watson *et al.,* 1999) with appropriate stand characteristics taken from Table 2 (RUE=0.5, Ω = 0.2) to determine the yearly value of TE = 1.7 g kg^{-1} in Eqn. (4) to derive the quantity of 880 mm of evaporated water that is associated with carbon gain. This quantity is deemed to comprise annual E_U along with a fraction of total interception loss that occurs in sunlight during canopy drying; 30% of annual $E_I = \Omega P_G$ = 320 mm, represents ~100 mm to be deducted for determining E_U as 780 mm. Transpiration is assumed to operate at ceiling levels throughout the year in this humid environment with $\hat{U}_U$ = 0.9, leaving 10% of available radiant energy to be disposed of as E_S with $\hat{U}_S$ = 0.7 representing an annual value of 60 mm; justification is based on Denmead (1984) who noted short-term equilibrium evaporation rates ($\equiv$ $\hat{U}_S$ = 0.79) from the litter-covered forest floor underneath *Pinus ponderosa* near Canberra. An annual total of 1160 mm for annual E_T compares favourably with a water balance determination of ~1100 mm for regrowth communities <40 years old (Langford *et al.,* 1980). This supports application of the procedure for mature conditions where computation is complicated by the greater uncertainty in characterisation caused by increased diversity.

A 100 year-old mature forest can be rated for height increase as 0.18 m yr^{-1} (Langford, 1976) with a stand LAI = 2.0 (Watson *et al.,* 1999). Conversion to dry matter productivity involves scaling with the previous ratio of dry matter/height, subject to adjustment for an effective doubling in basal area of the stand. An annual growth increment of 0.43 kg m^{-2} yr^{-1} is applied with an annual TE = 1.4 g kg^{-1} to derive 310 mm of growth-effective evaporative loss that comprises an uptake component (260 mm) and a fractional interception loss taken to be 16% in this case (50 mm) due to different canopy architecture with similar LAI between overstorey and understorey. Variation in RUE down to 0.4g MJ^{-1} was applied to accommodate greater maintenance respiration for the 100 year stand. E_S =70 mm is derived from an energy supply to the soil surface as 36% of that at canopy level for $\hat{U}_S$ = 0.2 because of mulch effects and reduced aerodynamic conductance of dense understorey. Annual E_T for mature forest is determined as 650 mm, assuming constancy of E_I between age classes. These considerations add up to a variation in annual water use of 510 mm during succession and support contentions for streamflow reduction by ~600 mm at 25 years after burning of mature stands of ash forest.

AGRICULTURAL DEVELOPMENT

Two case studies of agricultural development involving hydrological changes are summarised in Table 2, with indications of perturbations to salient characteristics that have resulted from management of vegetation for food and fibre.

Natural perennial grassland v improved annual grassland

The first case study of paired experimental catchments compares the ecological and hydrological consequences of conversion of natural grassland to introduced annual pasture in receipt of phosphatic fertiliser, a practice that gained widespread acceptance in undulating arable country from ~1955 (Dunin and Downes, 1962). In its natural state, this land comprised both woodland and grassland (Moore, 1970) with moderate rainfall and a Mediterranean type climate. Addition of fertiliser with trace elements, particularly molybdenum, generated vigorous growth of the annual pasture, with a threefold increase in productivity of the clover/grass mix over the natural perennial grassland at this site. An accompanying reduction in overland flow (Table 4) from 26 to 3 mm was a major limitation to this burgeoning grazing enterprise in hill country (de Laine and Vasey, 1961).

Table 4. Results of a paired catchment experiment at Bacchus Marsh, Victoria, using averaged data from the 4-year post treatment period to compare the catchment response under natural grassland (NG) with that using annual exotic pasture (IP) of subterranean clover and Wimmera rye grass (after Dunin, 1976).

Item	*Units*	*NG*	*IP*
Av rainfall	mm yr^{-1}	524	524
Av runoff	mm yr^{-1}	26	3
Peak discharge	mm $hour^{-1}$	2.4	10.4
Sorptivity(θ_0=0.2)	cm $minute^{-½}$	0.21	0.24
E_T/E_O(sp)	mm mm^{-1}	0.98	1.07

θ_0 – Initial soil water
E_O(sp) – Evap from Aust sunken pan ~ 0.9 E_{P-T}

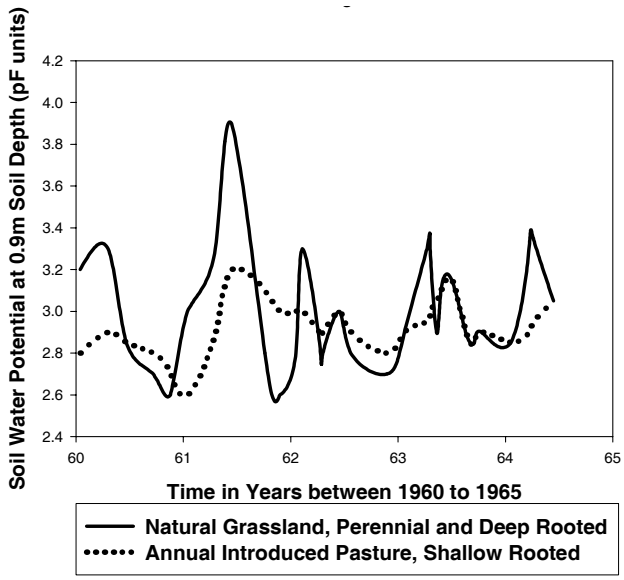

Fig. 4. *Dynamics in subsoil water potential (expressed in pF units Ψ log_{10} (cm)) at 0.9m soil depth for paired catchments, near Bacchus Marsh, with natural grassland designated as deep rooted species and annual improved pasture shown as shallow rooted species (after Dunin,1970).*

Moreover, the lost water harvest failed to reduce peak discharge with respective rainfall equivalent values of 2.4 and 10.4 mm hr^{-1}. When cleared of its native vegetation, erosion rates accelerated from much of this terrain (Downes, 1958), while erosion hazard, coupled with peak discharge as opposed to total quantity of overland flow, increased due to an absence of protective vegetation in the warm seasonal conditions associated with convective storms of high rainfall intensity. Further, outbreaks of dryland salinity have affected both water resources and land capability (Downes, 1972; Peck, 1978). The driving force for secondary salinity is accelerated deep drainage (Bettanay *et al.,* 1964), which is expressed by differences between communities in the regime of subsoil water content; a temporal pattern under natural perennial grassland with regular summer oscillation was indicative of uptake at this soil depth compared with annual pasture having an oscillation that is attenuated and irregular to reflect drainage for groundwater recharge (Fig. 4). This paradox of enhanced growth leading to an impaired resource base must be resolved to address the pervasive issue of enduring prosperity for agricultural enterprises.

A phase difference in the biological rhythm between communities is expressed in terms of the climatic variables in Table 2 that deal with T_{OPT} for seasonal function and its associated D, influencing TE. In this comparison of plant communities, these features affect growth and infiltration issues. A high optimal temperature for natural grassland ensures summer growth activity by C_4 pathway metabolism in the dominant species, *Themeda australis*. This biochemical attribute endows the high ITE that is assured in summer in temperate Australia but is lost when the temperature drops below 15°C (Hatch and Slack, 1966). Hence, summer growth progresses to a senescent sward in winter; this leads to a distinctive hydrological regime of a dominant discharge of clean water from overland flow and a small component of deep drainage serving as a leaching fraction. Summer activity of the dominant perennial grass ensures effective control of deep drainage through exhaustive soil water uptake from the root zone each summer (Fig. 4). A significant proportion of the sward consists of dead material across all seasons; this acts as an effective mulch which suppresses E_S when grazing pressure is light (Groves, 1974). Diminished uptake in winter and spring due to limited green leaf area (limited C_3 pathway species exist in the sward) combines with suppressed E_S to maintain low soil water deficits in surface soil during a period with abundant soil water. Infiltration rates are low and so a reasonable fraction of rain becomes runoff (5% in Table 3). Limited redistribution of this soil water gain is characterised by a depth profile of diminishing drainage flux within the root zone. A subsoil scavenged of soil water in the previous summer restricts vertical drainage at the base of the root zone in most seasons. The annual introduced pasture species have a temperate character, with T_{OPT} adapted to make growth in winter and spring through uptake that permits high rates of infiltration with an attendant reduction in runoff. Not all the infiltration is retained for soil water extraction despite high values for $\hat{U}_{U/S}$. The opportunity for exploiting infiltration gain is diminished by a root zone that is truncated compared with the perennial grassland and there is higher frequency of deep drainage events to increase recharge to groundwater. Following this seasonal change

in growth pattern, the discharge has been altered from overland flow to vertical drainage; species change involves replacement of a dominant summer perennial with temperate annual exotics.

Environmental degradation has accompanied this seasonal shift in growth activity in two ways. With perennial grassland lightly grazed, erosion is low and this enables year-round protection to discharge clean water. Vigorous summer growth enhances the protective grass cover to withstand erosion hazards imposed by peak discharge after the intense rainfalls associated with summer thunderstorms. Annual pasture, by comparison offers little protection to accelerated erosion even though annual runoff is much less but peak discharge rates are not mitigated. The dominant outflow changes to deep drainage, causing accelerated groundwater recharge to an aquifer network with low discharge rates; the resultant rise in water table levels is accompanied by salt in transition, which has a negative effect on both land capability and water quality.

Convential wheat cropping vs. crop management with supplemental N fertiliser

The second example evaluates a contemporary management of crop agronomy that has been responsible for significant increase in the national wheat harvest over the past two decades (Hamblin and Kyneur,1993). Two fields, each of 5 ha, were used for a comparative water balance study (Table 5).Yield was enhanced by addition of nitrogen (N) as urea and equivalent to 100 kg(N) ha^{-1} prior to tillering when soil water levels were high on August 6,1993 (60 days after sowing). Significant increases of 50% in above ground biomass (10.1 and 15.2 t ha^{-1}) (Table 5, Fig. 5b) and 80% in grain yield (3.8 and 6.8 t ha^{-1}) were achieved. (Smith *et al.,* 1998; Smith *et al.,* 2000). Crop improvement was accompanied by a marginal increase of 47mm in water use (≡ 12% of the respective seasonal totals of 350 and 397mm) that translated into the development of an even smaller difference of 32 mm in the soil water deficit at harvest (Table 5). The resultant difference between treatments in seasonal drainage from the root zone is minor at 11% (Table 5, Fig. 5a); 1993 seasonal drainage as ~20% of the seasonal rainfall ranks as approximately three times the 15-year average observed at this site for cropping conditions and an order of magnitude greater than under natural vegetation (Walker *et al*., 2002). Unlike the previous example in undulating terrain, deep drainage has been the dominant form of outflow in this flat terrain with 3% slope. An examination of the detailed time series for the seasonal course of a suite of variables relevant to growth and the water balance follows in seeking a resolution for the inconsistencies of substantial growth increments achieved without exercising drainage control and without great amounts of additional water use.

The pattern of cumulative rainfall diverged from that of total water use by both treatments $E_{T(N0)}$ and $E_{T(N+)}$ until the first week of October to indicate a phase of soil water excess with episodes of deep drainage (Fig. 5a). During this phase of abundant soil water, energy limits the rate of water use to <3 mm d^{-1} resulting in $E_{P-T} = E_{U/S} \approx E_S$. Despite marked differences in LAI, the patterns of $E_{T(N0)}$ and $E_{T(N+)}$ pre-October are comparable (Fig. 5b) to account for the similar drainage response observed between crops. However, in the post-September period when $3 < E_T < 6$ mm d^{-1}, convergence of E_T to P_G reflects the development of soil water deficits in both crops at the expense of drainage. Greater convergence of $E_{T\,(N+)}$ to P_G (Fig. 5a) indicates how the N-enhanced crop with greater LAI (N+) exercises superior control of soil water flow in the root zone in this phase of high atmospheric demand. This greater control was expressed in terms of 11 mm less in seasonal drainage and even more so in terms of a greater deficit of 32 mm at harvest. Any drainage control

Table 5. Water balance components for 1993 growing season at Wagga Wagga, New South Wales, to compare treatment effects of supplemental nitrogenous fertilizer (N0 and N+) on wheat water use, ET, and constituent processes of E_U and E_S. Seasonal Water Balance at Wagga Wagga, May 20–Nov 25, 1993 (mm)

Components		N0	Wheat treatments		N+
Seasonal rainfall, ΣP_G		417		417	
WU ΣE_T =	$\Sigma(E_U + E_I)$	350	145	397	209
$\Sigma(E_{U/S}+E_I)$	ΣE_S		205		188
SW change $\Delta W=\delta_{-9}+\delta_{9+}$	$\delta_{-9}=\Delta<0.9$m	-35	-25	-67	-41
	$\delta_{9+}+=\Delta>0.9$m		-10		-26
Deep drainage >0.9m, $\Sigma_{\mu 9+}$		93		82	
Residual error		9		5	

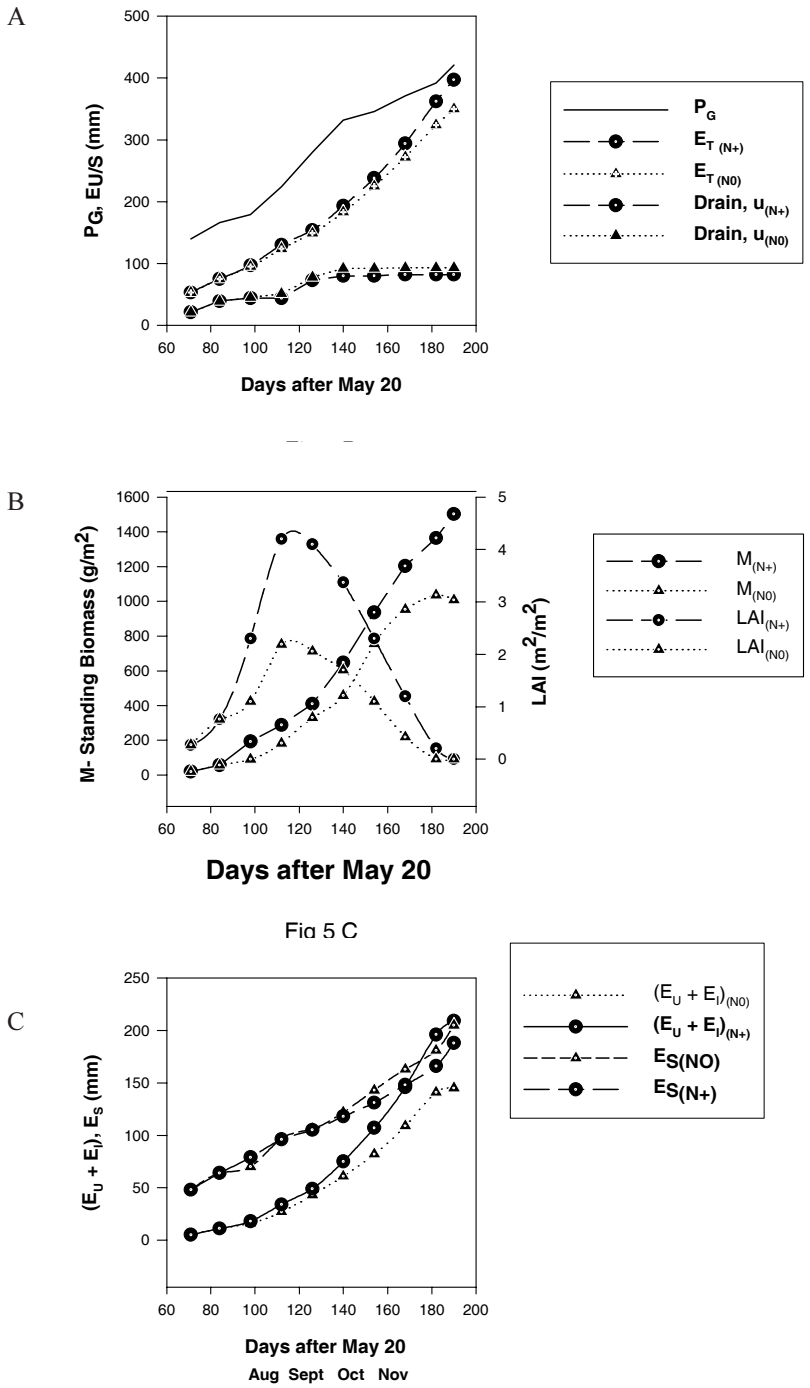

Fig. 5. *A. Seasonal progression at Wagga Wagga in 1993 for cumulative rainfall (P_G), total water use ($E_{T(N0)}$ and $E_{T(N+)}$) and drainage below 0.9m for two wheat crops ($\mu_{(N0)}$ and $\mu_{(N+)}$) with variation in application of supplemental nitrogenous fertilizer, N0 and N+, respectively. B. Seasonal course of cumulative standing biomass ($M_{(N0)}$ and $M_{(N+)}$) and leaf area index ($LAI_{(N0)}$ and $LAI_{(N+)}$) of both crops. C. Seasonal course of cumulative transpiration plus interception loss ($(E_U + E_I)_{NO}$ and $(E_U + E_I)_{N+}$) and direct evaporative loss from soil($E_{S(NO)}$ and $E_{S(N+)}$) from both crops.*

arising from this enhanced soil water extraction will be postponed until the subsequent season.

The patterns of cumulative transpiration plus interception loss, $(E_U + E_I)$ are offset from those of E_T by 40–50% (Fig. 5c). The seasonal total for $(E_U + E_I)_{(N+)}$ exceeds that for $(E_U + E_I)_{(No)}$ by 64 mm whereas those for E_T differ by 47 mm. The greater soil water uptake in treatment N_+ is driven by greater LAI but a compensating effect to suppress E_S through greater shading has meant that the combined soil water extraction for both evaporative processes in this treatment is tempered by 17 mm. The comparison of seasonal soil water decrement (Table 5) indicates that a 32 mm difference

is contributed by a lower soil water loss to drainage from the root zone in treatment N_+. A potential soil water deficit created by the requisite uptake of 64 mm for additional growth has been halved at harvest time due to the interacting influences of the increased growth to conserve soil water in the profile. Agronomic benefit achieved through greater uptake is not translated commensurately into hydrological control on flow processes.

Hydrological response as uptake for growth is summarised in the double mass curve (Fig. 6) describing the seasonal growth as a function of cumulative transpiration. The overall TE is remarkably similar between treatments at 7.11 ± 0.16 g DM/kg H_2O. Over the course of the season, both treatments followed a similar two-stage progression; in the early season, the enhanced phase of TE relative to the overall seasonal value is followed by a phase of convergence on to the final value. This shows that more growth was achieved through greater LAI and, hence, higher seasonal transpiration without any significant impact of N on TE. The greater LAI was accomplished through sustained ceiling rates for longer than in the control treatment (Table 2). Although this lack of TE response to N continues to be debated in agronomic circles, there is a precedent for the role of N in stimulating growth without changing the respective rates for carbon assimilation and transpiration. Wong *et al.* (1979) demonstrated that greater photosynthetic capacity caused by higher [N] in the canopy was accompanied by higher stomatal conductance. Greater rates of resource use delivered faster growth through greater carbon assimilation, balanced by a corresponding increase in transpiration.

Recourse to a simple description of growth as a function of water use and its efficiency has become commonplace to account for a wide range of crop growth response in terms of water use factors; such an approach deems that the full array of edaphic factors that contribute to variability in productivity is implicated to influence either the quantity of water use or its efficiency for conversion into harvestable product (de Witt, 1959; Passioura, 1972; Tanner and Sinclair, 1984). This case study is a timely reminder that water relationships offer a convenient linkage between the water and carbon cycles. The impact of elevated [N] in the canopy derived from fertiliser was captured with increased LAI that was expressed as increased seasonal transpiration. The additional soil water uptake necessary to achieve a 50% increase in growth is explainable through Eqn. (4) (From Table 2, TE = 7.0 g kg^{-1}, $_*$ 64 mm ≡ 4.5t ha^{-1}). The hydrological consequence on soil water flow of this improved agronomy has been modified in its magnitude and deferred in its timing. Incremental uptake of 64 mm translates into an equivalent seasonal decrement in soil water of 32 mm; such a reduction in deep drainage would be unlikely to occur before the following crop season and then only if there were sufficient rainfall to overcome the soil water deficit and generate drainage flow.

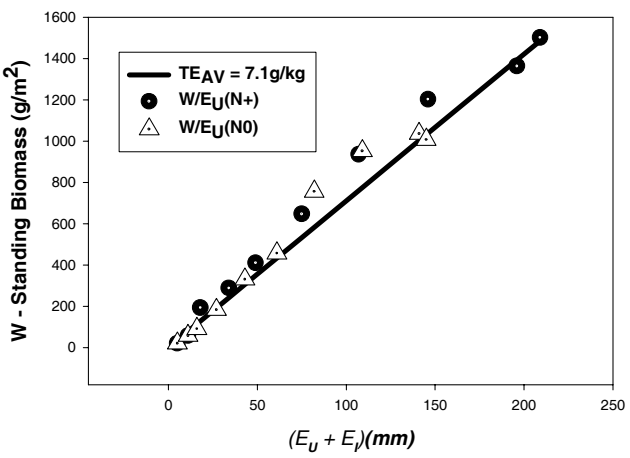

Fig. 6. *Double mass plotting of cumulative standing biomass with cumulative transpiration and interception loss. The seasonal average of transpiration efficiency, TE_{AV}, is superimposed for reference.*

Towards integrated catchment management

This review of four case studies of hydrological change emphasises how catchment management must seek an acceptable balance between water resources and plant productivity for food and fibre. A shift in either direction can impair the resource base and jeopardise the long-term viability of the management strategy. Too much plant production can deny water outflow altogether and risks salt accumulation in the root zone, so that agricultural productivity will diminish. Alternatively, excessive water outflow can degrade the edaphic environment with flooding and erosion and so may impede a critical plant function that controls outflow in quantity and quality. These considerations set limits to ecological manipulation before counter-productive responses of resource degradation hold sway.

Natural ecosystems progress towards maturity through ageing; this results in parsimony in the rate of resource use. This was evident in the studies of ash forest and of natural grassland with short-lived values of $\hat{U}_{U/S} = 0.8$; trends with age were similar but the response time was shorter than with forest. Communities in a mature state are ideal for water harvesting in upland forests and in grassland on undulating country in the lowlands. Fire, however, reduces water availability in both communities. The wildfire of 1939 attained temperatures in excess of 300°C; this interrupted successional progress (Craig, 1964) and resulted in a

rejuvenated community of high vigour and much reduced water harvest (Langford, 1976; Kucerza, 1987). Control burns, designed to reduce fuel loads on the forest floor, are cooler and minimise damage to the overstorey thereby enabling the ageing trend to proceed. Water harvest is diminished, but not to the same extent as with rejuvenation although the loss of control on E_S through regular litter removal will reduce streamflow. Fire in natural grassland led to a 30% increase in $\hat{U}_{U/S}$ to 1.0 and an equivalent reduction in streamflow that lasted for about one year (Dunin, 1989). Grazing affects the amount of water harvested through diminished soil water conservation. An absence of mulch and a rejuvenated sward in a grazed community of natural grassland have increased $\hat{U}_{U/S}$ to 90% of that for improved pasture (Dunin, 1970).

Intervention in natural ecosystems by species change in forestry and for pasture has resulted in higher productivity at the expense of water harvest. The paradox is that changed plant function which has been successful in delivering higher growth, fails to afford environmental protection because of loss of control on sediment and solute transport. For pine plantation, the danger of water contaminated with sediment tends to be associated with the establishment and harvesting phases. Hence, ensuring prudent planting and harvesting techniques is essential in protecting a water resource now diminished in quantity. Agricultural development is more complex; a persistent erosion hazard is compounded by a potential problem of solute transport with far reaching ramifications for both land and water conservation. River contamination, mainly with salt from agricultural sources, has become so pressing that community demands for reform in agricultural land management now have high priority. Achieving on-farm control of material transport while still maintaining profitable enterprises in food and fibre production has been a recurrent issue for decades but contemporary outbreaks of salinity and acidity, currently accelerating in farmland, have underlined the urgent need for a novel ecology that redresses conservation problems through high productivity (Downes, 1959).

Technological advances in crop and pasture agronomy for productivity and profit have been hailed as providing a buffer against deep drainage to ward off escalating problems of soil salinity and acidity (Singh *et al*., 2002). One of the present case studies demonstrates a 50% increase in productivity for a marginal change in buffering capacity against drainage. This lack of flow control can be attributed mainly to a shallow root zone associated with the suite of annual species used extensively in agricultural practice. A case for reinstating perennials in the agricultural landscape can be mounted on grounds of an extended root zone that serves the conservation cause with active growth in summer to control erosion and effective buffering against deep drainage implicated in degradation of both soil salinity and acidity. A series of Australian programmes and studies is under way to explore the role of perennials in reclaiming saline land, as in Montana, USA, with catchment re-vegetated by the herbaceous perennial legume lucerne, *Medicago sativa* (Miller *et al*., 1981). This species has been the focal point for herbaceous re-vegetation in Australian crop rotations with as much as a three-fold increase in soil water extraction over that by annual crops (Ward *et al.,* 2001; Ridley *et al.,* 2001). This removal of accrued subsoil water during the lucerne phase of the rotation provides drainage control akin to that of natural ecosystems (Dunin *et al.,* 2001) without major compromise to crop yields (McCallum *et al.,* 2001; Latta *et al.,* 2001). Stemming the spread of salinity requires an exploitative phase of water use to deny groundwater accession and restore water table levels to pristine conditions. Woody plantations of either exotic or natural species are effective in eliminating groundwater recharge within their local zone of soil water extraction; lateral extension of uptake beyond the canopy drip line is minor (Stirzaker *et al.,* 1999) and this extension is determined as the length equivalent of 1–2 times canopy height. Enhanced interception loss and rapid root penetration into subsoil are characteristic of plantations of exotic species, such as tagasaste (Lefroy *et al.,* 2001) and eucalypts (White *et al.*, 2002). In both of these studies, uptake of groundwater from the capillary fringe accelerated the process of groundwater reduction. Not all species are equally efficient in abstracting groundwater, which indicates species variation in tolerance to oxygen limitation for root functioning. However, any lowering of the local water table generates a lateral influence to reduce groundwater discharge. Evaluation of this effect has involved comparison of groundwater uptake by a plantation with rates of recharge below adjoining farmland on a hillslope discharging saline groundwater to streamflow (Dunin, 2002). In this study to restore the natural water balance, ~20 % of forest plantation area was optimal for arresting the spread of salinity so that reclamation of salt scalds could proceed. A generalised appraisal of the trade-off between crop productivity and drainage control by plantations offers a basis for assessing the potential for control of salinity across a range of terrain and geometry in groundwater flow (Stirzaker *et al.,* 2002). These insights offer the ingredients of a novel ecology to balance competing demands in land management.

An integrated approach to water conservation is critical at the scale of the river basin where the balance in catchment outputs shifts towards plant productivity with downwards progression along a transect of reducing altitude and rainfall. Upland, the discharge of freshwater as perennial streamflow

takes precedence over the competing industries of forestry and high country cattle grazing. Regulated rivers, diverted for both urban water supply and irrigation, require reliable flows of clean water. In the lowlands, contamination of the resource has become a problem through return flow from irrigation as well as through transport of materials in the meagre flows from semi-arid tributaries under dryland agriculture. Remedial action is directed at solute flows through hydraulic control of return flow from irrigation and urban discharge. Attention to sediment control in tributary flow is now being reinforced with biological measures to curtail salt flow. Progress in conservation and resolution of competing pressures may well be facilitated through the understanding gained in these case studies.

Concluding remarks

A generation of data acquisition on gaseous exchange is the basis of a simple conceptual framework to link plant growth with water use; this is critical for an understanding of contemporary issues of the effects of changes in land use on water resources. This framework identifies 11–17 distinguishing features of an ecosystem to describe plant function in the use of water, carbon and light resources for growth. A shift in the values of these features has been explored in four case studies of experimental catchments, in each of which outflows were altered by changes in ecology which improved plant productivity. Interest in these cases of hydrological change arises from a need to reconcile counterintuitive responses to changing plant productivity. Three cases of man's intervention for greater plant productivity have generated a range of hydrological responses but all threaten water conservation. The other case of wildfire had an intriguing outcome of reduced forest streamflow.

That greater growth demands increased water use is axiomatic in agronomy (Briggs and Shanz, 1914) but the hydrological outcome is generally a reduction in streamflow (Hewlett and Hibbert, 1967; Bosch and Hewlett, 1982). Yet, trebled pine productivity at Lidsdale was achieved without changes in annual evapotranspiration, $E_{U/S}$, over that by the natural community of dry sclerophyll eucalypt forest. The interception loss, E_I, by pine (5–10% P_G) was greater and accounted for the reduction in streamflow but fell far short of the necessary carbon assimilation to account for differences in annual growth rate. This can be explained as a phase difference in the annual patterns of $E_{U/S}$; pine is better adapted to make effective use of soil water uptake, E_U, at low temperatures in winter and spring. A seasonal difference in plant function, T_{OPT}, between natural perennial pasture and improved annual pasture was critical in changing outflow following a trebling of pasture production. In this case, greater seasonal E_U by the annual pasture in winter and spring exceeded that by natural grassland in summers generally deficient in rainfall. Thus, overland flow was reduced but the shallow root zone of the annual pasture, unable to cope with additional infiltration, led to accelerated deep drainage as a hydrological change which beset the agricultural environment with salt in transition. Efforts at enhanced agricultural production have been rewarded with productivity increases that can be rated as 25–50 mm of incremental E_U per t ha^{-1} of wheat grain harvest. These greater levels of uptake do not translate into commensurate increases in $E_{U/S}$ because of the offsetting effects of soil water conservation afforded by additional herbage in suppressing E_S. Instances where additional E_U is compensated by reduced E_S may lead to zero mitigation deep drainage in the presence of increased growth. The case for restoring the natural water balance through ever-increasing productivity of annual ecosystems lacks hydrological support.

That streamflow falls after forest wildfire contradicts conventional wisdom on forest clearing (Bosch and Hewlett, 1982) and even a previous report on eucalypt burning (Brown, 1972). The physiological explanation of this anomaly may reflect the control of transpiration by trees over 100 years old (Watson *et al.*, 1999). Juvenile development of eucalypts from seedlings can proceed with high $\hat{U}_U$, in contrast to early phases of rejuvenation through epicormic regrowth. This is a timely reminder of the virtue, for water harvesting, of moribund plant communities although management to preserve the mature state with limited function still provokes controversy.

A policy of integrated catchment management must define areas of water harvest involving the preservation of natural ecosystems with assured fire protection. For local water harvest, lowland, natural grassland free of grazing and fire can emulate the role of upland mature forest. Multiple land use with plant production prioritised will reduce the quantity of water, perhaps with a deterioration in water quality in respect of solutes and material transport of sediment. Restoration of the natural water balance may be critical in remediation; to this end, reinstatement of perennials in agricultural systems is advocated. The challenge still remains to optimise the productivity of a combination of perennials and annuals to produce the required outflow control.

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