NEFA BACKGROUND PAPER

CLEARING OUR RAINFALL AWAY

Dailan Pugh, February 2017

> *This attractive force of the forests on this island is such that a field in an uncovered situation close to them often suffers a lack of rain whereas it rains almost all year long in woods that are situated within gunshot. It is by destroying part of the trees crowning the heights of this island that one has caused most of the streams that watered it to dry up. I attribute to the same lack of foresight the notable diminishing of the streams and rivers in a large part of Europe.*
>
> **Bernardin de Saint Pierre 'Etudes de la Nature' 1784-8,**
> describing the impact of forests on rain and streamflow in Mauritius (Andreassian 2004).

This review was initiated in response to the question "How do forests affect rainfall?". In the process of reviewing the available scientific literature it became apparent that there is now an overwhelming abundance of evidence that deforestation has had a profound impact on regional climates, including in southern and eastern Australia, and a growing effect on global climates. The answer is "profoundly".

Deforestation accounts for as much as a third of total anthropogenic CO^2 emissions since 1850 and thus is one of the principal contributors to global warming through the greenhouse effect. Though deforestation also has direct biogeophysical effects on rainfall, wind and temperature of similar amplitude, that in some cases is being mistakenly attributed to CO^2 emissions, and in others may be masking the full impacts that CO^2 emissions are having. It is the biogeophysical effects of deforestation that are the subject of this review.

Terrestrial climates evolved over hundreds of millions of years as vegetation colonised the land and created conditions more suitable for its own growth, modifying temperatures, conserving moisture and enhancing rainfall as it progressed inland. Human civilisations emerged within the climate created by the vegetation, modifying the vegetation to suit their purposes, sometimes with dire climatic consequences.

It is well known that climate influences vegetation, and while it has long been recognised by some that vegetation influences climate, we are still only beginning to understand the complexity and scale of the mechanisms involved.

At its simplest, the basis for the hydrological cycle is that water is evaporated from the ocean into the atmosphere, the water vapour is carried by winds across the land until it condenses and falls as rainfall, with excess water entering streams and travelling downhill back into the oceans. All the terrestrial water contained in glaciers, lakes and soil could be depleted by global river runoff in just a few years if it was not replenished by atmospheric flows from the ocean. Rainfall is an outcome of rising atmospheric moisture cooling and condensing around particles (mostly organic) in the air to form water droplets which grow by colliding and merging to create larger droplets until gravity takes over and they fall to earth.

Vegetation does not just respond to rainfall, it actively generates its own. It recycles water from the soil back into the atmosphere by transpiration, creates the updrafts that facilitate condensation as the warm air rises and cools, creates pressure gradients that draw moist air in from afar, and, just to be sure, releases the atmospheric particles which are the nuclei around which raindrops form.

Forests have been described as 'biotic pumps' driving regional rainfall because their high rates of transpiration return large volumes of moisture to the atmosphere and suck in moisture laden air from afar.

While most of our rain originates from evaporation of the oceans, it is estimated that 40% of the rain that falls on land comes from evaporation from the land and, most importantly, from transpiration by vegetation. Recycled water vapour becomes increasingly important for inland rainfall.

Having created and attracted the water vapour, the plants then make it rain. Plants emit volatile organic compounds (VOCs), such as plant scents and the blue haze characteristic of eucalypt forests. They play an important role in communication between plants, and messages from plants to animals, and also between plants and moisture-laden air. They oxidise in the air to form the cloud condensation nuclei around which water drops form.

The transpiration of vegetation also results in evaporative cooling whereby the surface heat is transferred to the atmosphere in water vapour. The resultant clouds also help shade and cool the surface.

Pielke (2001) concluded "*In the context of climate, landscape processes are shown to be as much a part of the climate system as are atmospheric processes*".

There is abundant scientific evidence that deforestation and degradation of vegetation causes significant reductions in rainfall by:

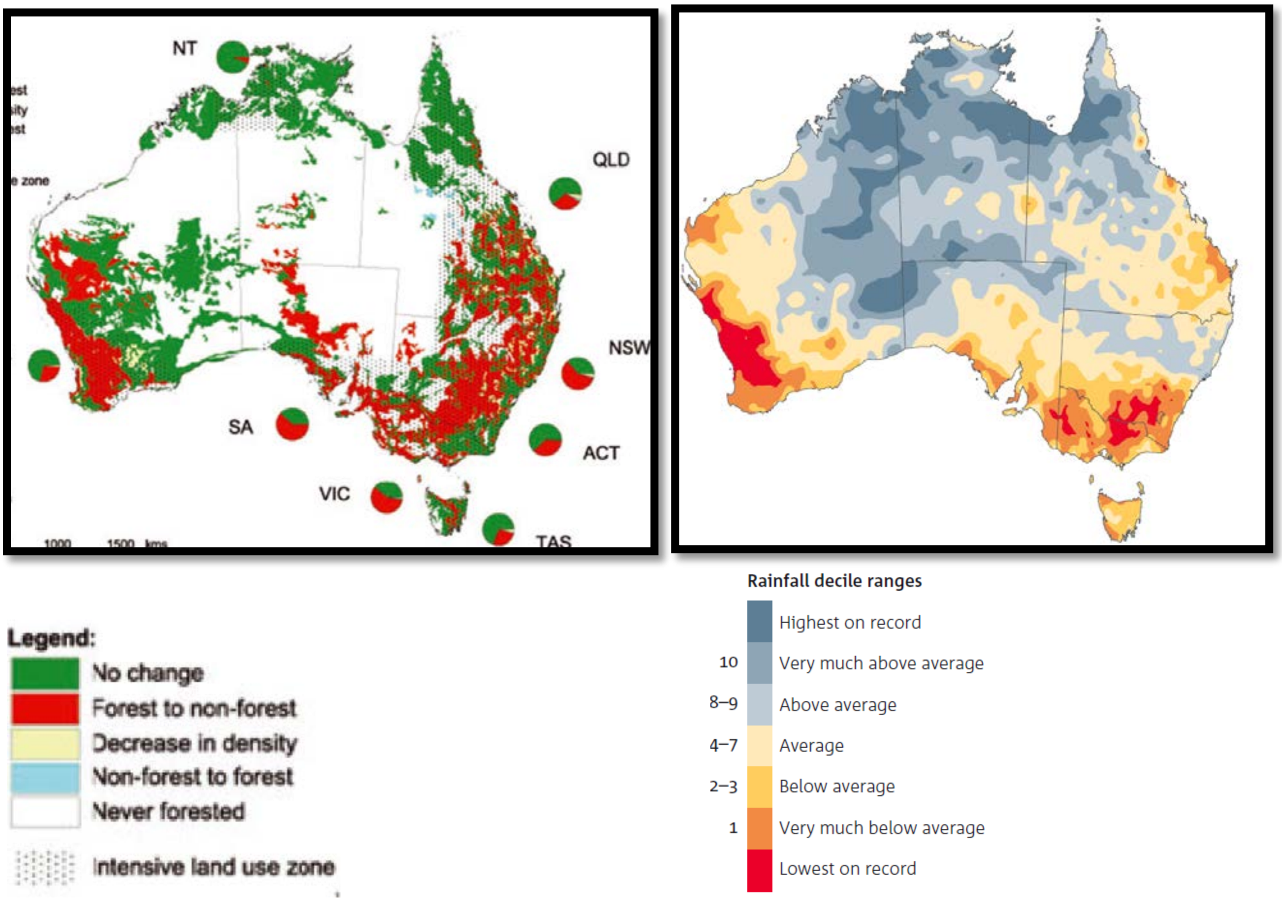
- reducing the recycling of rainfall to the atmosphere by transpiration
- reducing the drawing in of moist coastal air
- reducing updrafts of moist air
- reducing rooting depth and the recycling of deep soil moisture
- increasing loss of water from the land by runoff
- reducing the organic aerosols necessary for the condensation of rain drops.

Deforestation has other climatic impacts; the reduction of surface roughness increases wind speeds, the reduction of transpiration increases temperatures by reducing evaporative cooling and cloud cover, and the burning of vegetation releases soot to the atmosphere where it can reduce rainfall.

There is conjecture that the increased frequency of extensive fires following the arrival of Aboriginal Australians some 50,000 years ago significantly reduced tree cover and thus rainfall in some drier regions, possibly resulting in reduced penetration of monsoon rains into central Australia and increasing aridity.

There is no doubt that the arrival of Europeans just over 200 years ago began the widespread deforestation of most of our most productive lands, and significant degradation of vast tracts of native vegetation by logging and grazing. This has had a profound impact on our rainfall, contributing to significant declines in the most heavily cleared regions in southern and eastern Australia.

It has been estimated that since European settlement, land clearing in eastern Australia has directly resulted in an average summer rainfall decrease of 4-12%, a warming of around 0.4-2°C, and an average 9% increase in surface wind speeds. This conforms with studies from around the world that land clearing significantly affects rainfall and climate.



Comparison between deforestation and rainfall declines: LEFT: The land-cover map of Australia showing changes in native vegetation since European settlement (Source Deo 2011) RIGHT: Rainfall deciles for April-September1997-2013 relative to 1900-2013 (Source: Braganza et. al. (2015).

South-west Western Australia provides a clear example of the folly of over-clearing vegetation. By 1950 30% of the arable area had been cleared, increasing to 72% by 1980. In the mid-1970s a clearing 'tipping-point' appears to have been reached and the region experienced a step-wise change in climate manifesting itself as a rapid 15–20% decrease in rainfall and an associated 50% decrease in runoff into Perth's drinking water catchments. Since 1996 this decline in rainfall from the long-term average has increased to around 25%. In 2001 there was another shift with a further 50% reduction in runoff.

Studies have concluded that in south-west Western Australia up to 50-80% of the rainfall decline since 1970, and 50% of the observed warming since European settlement, could be attributed to land-clearing. Despite the reduction in rainfall, groundwater has risen on cleared lands turning most of the streams saline and affecting over 500,000 hectares of previously productive agricultural land. And while the conversion of oldgrowth forest to regrowth is having the effect of increasing transpiration, it is not compensating for the losses, and with declining rainfalls the water stress is killing trees and drying catchments.

Across drier areas of Australia the removal of deep rooted forests and woodlands has caused watertables to rise, allowing long-buried saline ground-waters to rise towards the surface, with the resultant dryland salinity affecting millions of hectares. This has turned many of our rivers saline, caused widespread degradation of native ecosystems and agricultural lands, destroyed infrastructure, and diminished biodiversity. And it can take decades or centuries for the impacts to manifest. Some 7.5 million hectares of NSW's agricultural lands are considered at risk.

The first section of this review seeks to identify the principal means by which deforestation affects climate, particularly rainfall. In the second section of this review Australia is considered as a case-study of the impacts that deforestation, and the use of native vegetation for hunting, grazing and logging, has had on regional climates.

History is littered with failed civilisations that cleared too much vegetation and changed the climate to one unfavourable for their own survival, such as the Nasca of southern Peru and Anasazi of south-west USA. Clearing and degradation of native vegetation has now progressed to the stage where regional impacts are turning into global impacts. We cannot afford to continue to ignore the climatic consequences that past and ongoing forest clearing and logging are having on Australia, the driest inhabited continent on earth

While recently there has been a focus on the impacts of greenhouse gasses on climate change, it is evident that deforestation plays a significant role in many of the climate changes currently underway, we ignore these impacts at our peril. Pitman *et. al.* (2012) modelled variable changes in rainfall due to deforestation, finding that in regions subjected to significant land-use change "*the impact of landscape change on temperature and some hydrometeorological variables can be similar in magnitude to a doubling of atmospheric CO^2", and* that "*land cover change would offset the impact of elevated CO^2. Surprisingly, this also included partially offsetting a CO^2 induced increase in rainfall over S.E. Asia in three of the four models*".

In relation to the significant effects of Land Use-Land Cover Change (LULCC) de Noblet-Ducoudré *et. al.* (2012) caution:

> *Increased concentration of greenhouse gases in the atmosphere, and the subsequent changes in sea surface temperatures and sea ice extent, are often used as the main drivers of climate change also over land. Our results suggest that such an assumption leads to erroneous conclusions regarding the land surface impacts of climate change in regions where LULCC has been significant. LULCC affects a number of variables to a similar magnitude, but of opposite sign, in increasing greenhouse gas concentrations. LULCC therefore has the potential to mask a regional warming signal, with the resulting risk that detection and attribution studies may miss a clear greenhouse signal or misattribute a greenhouse signal if LULCC is poorly accounted for.*

Current climate changes are primarily consequences of deforestation, injection of massive volumes of aerosol pollutants into the atmosphere and the release of greenhouse gasses such as carbon dioxide. Into the future greenhouse gases will become the increasingly dominant influence, though at this time in our history it is apparent that we can significantly modify the climate changes underway by retaining and restoring our natural vegetation and reducing biomass burning. This will buy us time to redress pollution caused by our use of fossil fuels.

Eiseltová *et. al.* (2012) consider:

> *The water cycle is akin to the 'bloodstream' of the biosphere. Returning water to the landscape and restoring more natural vegetation cover is the only way to restore landscape sustainability. More attention in present-day science needs to be devoted to the study of the role of vegetation in the water cycle and climate amelioration. Restoration of a more natural vegetation cover over the landscape seems to be the only way forward.*

CONTENTS

1. VEGETATION'S ROLE IN GENERATING RAINFALL

Vegetation plays a significant role in climatic processes, from creating microclimates beneath their canopies, to modifying regional winds and temperatures, to enhancing rainfall, and changing atmospheric heat and moisture fluxes at continental scales. There is now abundant evidence that deforestation is having a significant impact on regional climates, and the reasons for this are becoming increasingly apparent.

Far from being passive, vegetation plays an active role in its partnership with climate (Zeng and Neelin 2000). Across the semi-arid Sahel in central Africa, the forests and woodlands of southern Australia, and the mighty Amazon rainforests, clearing, logging and burning of natural vegetation is causing a considerable increase in temperatures, decrease in evapotranspiration and decrease in rainfalls. As observed by Fu (2003):

> *Both the observational and theoretical studies have proved that the destruction of natural vegetation cover, such as destructive lumbering of forests and over cultivation and overgrazing of grassland has been one of the major causes for the deterioration of regional climate and environment.*

At the site level, compared to cleared areas, it is apparent that forests can create their own microclimate, with more stable temperatures (warmer on cold winter nights and cooler on hot days), and with moister soils and higher humidity in dry times (Meher-Homji 1991). Vegetation, and particularly forests, can affect regional climates by:

- transpiring moisture from the ground into the atmosphere to form clouds and generate rainfall
- providing a large area of leaves and other surfaces for evaporation of moisture back into the atmosphere
- creating areas of low pressure by evapotranspiration that generate winds and draw in moisture from afar
- having an 'evaporative cooling' effect by absorbing solar energy and converting it into latent heat held in water vapour through evapotranspiration
- emission of organic aerosols, and volatile organic compounds that oxidise to form aerosols, that act as cloud condensation nuclei around which water drops form
- increasing air turbulence, causing drag on the air and reducing wind speed, increasing transfer of moisture into the air, causing updrafts and rain
- tree canopies harvesting water directly from wind and clouds, particularly in coastal and mountainous country.

The influence of vegetation is related to many variables; the prevailing climate, the vegetation type and structure, its extent, the season and time of day. It is forests. with their large canopy volume, massive evapotranspiration, deep roots and protected microclimate that are the most significant terrestrial drivers of regional climates.

Clearing vegetation can reduce rainfall by:

- reducing evapotranspiration and atmospheric moisture, causing a decrease in convective updrafts, clouds and the drawing in of moist air from afar;

- potentially increasing albedo (reflection of solar energy from the earth), having a cooling effect and causing a decrease in convective clouds;
- increasing runoff and reducing the availability of soil moisture for evapotranspiration;
- reducing rooting depth and the ability of vegetation to tap into, and recycle, groundwater;
- reducing vegetation height and surface roughness, increasing wind speed while reducing the ability of wind to capture moisture from canopies and the generation of updrafts;
- increasing surface sensible heat fluxes and decreasing latent heat fluxes, resulting is a reduction in evaporative cooling and raising the surface air temperature, causing drying; and,
- reducing organic aerosols and volatile organic compounds, and thus the availability of cloud condensation nuclei.

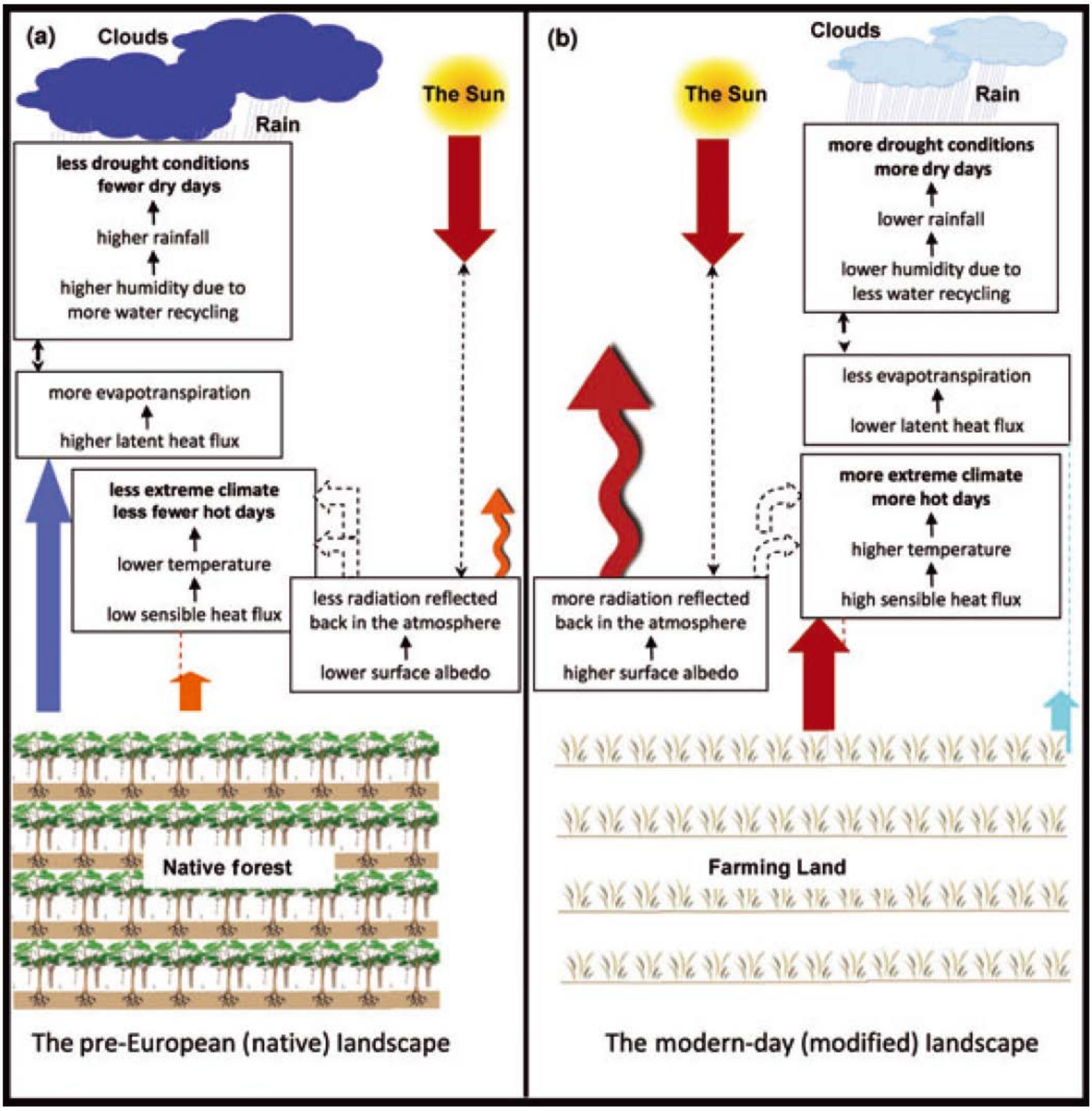


Figure 3 from Deo (2011). The impact of vegetation-cover change on surface energy balance, hydrological cycle and climate for two hypothetical landscapes: (a) pre-European (native) landscape, and (b) modern-day (modified) landscape. The coloured arrows show various energy/heat fluxes and black arrows show consequence of events or processes

An array of parameters that influence climate have now been identified in scientific studies as being significantly affected by deforestation, including evapotranspiration, vegetation rooting depth, surface roughness, canopy height, leaf area, stomatal resistance, humidity, wind, soil moisture, the ratio of latent/sensible heat, albedo, cloud cover, and snow cover (variously Shukla *et. al.* 1990, Nobre *et. al* 1991, Betts *et. al.* 1996, Claussen 1998, Zeng and Neelin 2000, Taylor *et.al.* 2002, Findell *et. al.* 2007, Findell *et. al.* 2009, Foley *et. al.* 2003, Foley *et. al.* 2003b, McAlpine *et. al.* 2009, Lawrence and Chase 2010, Bagley 2011, Kala *et. al.* 2011, Spracklen *et. al.* 2012, Pitman *et. al.* 2012, de Noblet-Ducoudré *et. al.* 2012, Andrich and Imberger 2013).

There are now numerous assessments, based on research and/or modelling, that agree that over the past few centuries and decades deforestation (Land Cover Change) has had significant biogeophysical impacts on rainfalls and/or temperatures in the regions subject to significant deforestation, for example:

> Charney 1975, Sud and Smith 1985, Claussen 1998, Shukla *et. al.* 1990, Meher-Homji 1991, Nobre *et. al* 1991, Giambelluca *et. al*. 1999, Hoffmann and Jackson 2000, Zeng and Neelin 2000, Zang et. al. 2001, Pielke 2001, Taylor *et. al.* 2002, Foley *et. al.* 2002, Lyons 2002, Gordon *et. al.* 2003, Foley *et. al.* 2003b, Narisma and Pitman 2003, Fu 2003, Hatton *et. al.* 2003, von Randow *et. al.* 2004, Pitman *et.al.* 2004, Miller *et. al* 2005, Huang *et. al.* 1995, Brovkin. *et. al.* 2006, Guo *et. al*. 2006, Makarieva and Gorshkov 2006, Timbal and Arblaster 2006, Findell *et. al.* 2007, Lam *et. al.* 2007, Syktus *et.al.* 2007, McAlpine *et. al.* 2007, Chapin III *et al*., 2008, Ramanathan and Carmichael 2008, Findell *et. al.* 2009, Pitman *et. al.* 2009, Sheil and Murdiyarso 2009, Makarieva *et. al.* 2009, McAlpine *et. al.* 2009, Makarieva and Gorshkov 2010, Lawrence and Chase 2010, Davin and de Noblet-Ducoudré 2010, Adams 2010, Deo 2011, Bagley 2011, Kala *et. al.* 2011, Ban-Weiss *et. al.* 2011, Nair *et. al.* 2011, Notaro *et. al.* 2011, Kovářová *et. al.* 2011, Lee *et. al.* 2011, Spracklen *et. al.* 2012, Pitman *et. al.* 2012, Eiseltová *et. al.* 2012, Tavares 2012, de Noblet-Ducoudré *et. al.* 2012, Rahgozar *et. al.* 2012, Wyrwoll *et. al.* 2013, Andrich and Imberger 2013, Luyssaert *et al*. 2014, Chen and Dirmeyer 2016.

The regional impacts of deforestation can be amplified during drought conditions (i.e. Bagley 2011, Pitman *et. al.* 2012).

The thinning of native vegetation, including by burning and grazing, can have proportional impacts similar to clearing (i.e. section 2.1).

The conversion of forests to regrowth has a distinctly different impact as the regrowth increases transpiration of soil moisture to the atmosphere, which reduces runoff and theoretically increases atmospheric moisture. Though logging also changes the structure of the forest (reducing its surface roughness and rooting depth) as well as causing changes in energy balances and the interior microclimate, all of which would have negative impacts on rainfall. While the effect of regrowth on runoff has been extensively studied (see section 2.4), no study of the effect of regrowth on regional rainfalls was located.

The case study of south-west Western Australia (section 2.4) shows that when combined with declining rainfalls, the increased transpiration of regrowth can have disastrous consequences for regional water supplies and the health of the forest.

In subsequent sub-sections this review considers in detail the impacts that deforestation has on climate, in relation to the principal attributes of evapotranspiration, energy fluxes, vegetation surface roughness, aerosols and soil moisture.

Another impact of deforestation having long-term climatic impacts is the release of large pulses of carbon dioxide to the atmosphere, as carbon stored in biomass such as trees and soil is released as the biomass is burned or allowed to decompose, accounting for as much as a third of total anthropogenic CO^2 emissions since 1850 (Bagley 2011). This review does not dwell on climate changes underway due to increasing atmospheric CO^2, but rather aims to identify the direct biogeophysical effects of deforestation on climate.

The surface of the earth has 130Mkm^2 of ice-free land. It is estimated that worldwide human activities have directly affected around 100Mkm^2 of this, leaving less than 30% of the land surface largely untouched, of this between 23 and 38Mkm^2 (18-29% of the land surface) has been deliberately converted, mainly by deforestation, for agriculture, infrastructure and urban use (Luyssaert *et al*. 2014). It is evident that outside the polar regions a large portion of the lands that have not yet been identified as significantly affected are the world's arid lands, which may themselves be partially attributed to the impacts of earlier civilisations (i.e. Claussen 1998, Johnson *et. al.* 1999, Brovkin 2002, Foley *et. al.* 2003, Fu 2003, Miller *et. al* 2005, Makarieva and Gorshkov 2010, Beresford-Jones *et. al.* 2009, Notaro *et. al.* 2011, Wyrwoll *et. al.* 2013).

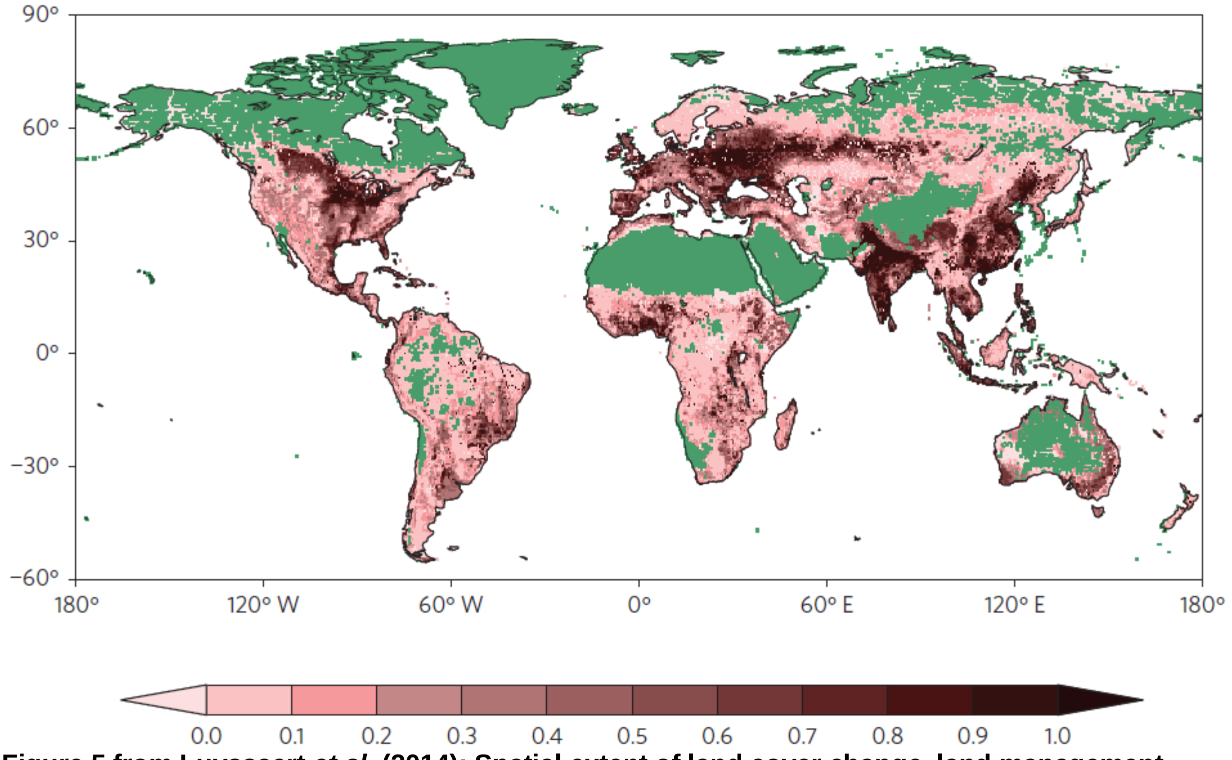


Figure 5 from Luyssaert *et al*. (2014): Spatial extent of land cover change, land management, wilderness and non-productive areas (Supplementary Section 2.3).Wilderness and non-productive areas are shown in green and represent land largely unaltered by humans in recent times. The remaining land is used for producing food, fibre and fuels, and for hosting infrastructure. The colour scale represents the fraction of each grid cell for which the original plant cover was converted. Dark colours indicate regions where most of the original plant cover was converted; these regions are the subject of typical land cover change studies. The light colours show areas for which land cover change is low, but which are nevertheless under anthropogenic land management.

There have been a large number of assessments of the likely impacts of anthropogenic Land Cover Change (LCC - clearing of native vegetation for crops, pasture or houses), and to a small extent Land Management Change (LMC - change off vegetation by logging, grazing and/or fire), on both regional climates and the world's climate. Regrettably the modelling studies use highly variable baseline data, limited variables, different assumptions of consequences, and mostly fail to account for the more extensive areas subject to degradation due to grazing, logging or increased fire regimes, and thus deliver highly variable outcomes (i.e. Pitman *et. al.* 2009, de Noblet-Ducoudré *et. al.* 2012, Luyssaert *et al*. 2014).

While some of the data is coarse, models simplistic, variables unaccounted for, and assumptions questionable, the modelling, and testing, has enabled insights into the inter-relationship between climate and vegetation. For example, from their comparison of 7 models de Noblet-Ducoudré *et. al.* 2012 found a number of robust common features, including that the changes in response to deforestation depend almost linearly on the amount of trees removed.

In general the impacts of deforestation on a global scale are often considered relatively insignificant because of the overwhelming influence of the oceans, or because minimal measures of LCC have been used in assessments (i.e. Findell *et. al.* 2007, Pitman *et. al.* 2012, Chen and Dirmeyer 2016). Though a variety of modelling studies have still identified significant global effects from LCC (i.e. Brovkin. *et. al.* 2006, Findell et. al. 2009, Luyssaert *et al*. 2014).

The complex feedback systems contributing to rainfall can come under increasing stress due to the degradation of vegetation, sometimes resulting in sudden catastrophic changes when an event triggers regime shifts. McAlpine *et. al.* (2009) consider:

> *Climate changes due to increased anthropogenic greenhouse gases coupled with land surface feedbacks appears to be amplifying the natural climate variability and has the potential to tip Australia's climate, especially in southeast Australia, into a new regime of more extensive, frequent and severe droughts. The term 'tipping' refers to a critical threshold at which a small change in the control parameters can alter the state of the climate system*

Excessive clearing has been associated with the downfall of many past civilisations. We need to learn from the lessons of history, understand and acknowledge the consequences of deforestation, and stop the desertification of Australia.

1.1. Evapotranspiration

The atmosphere receives vast inputs of water vapour as evaporation from the oceans and land, as well as transpiration by vegetation. This water vapour is returned to earth as rainfall, with the water in the atmosphere turned over about 34 times every year.

Evapotranspiration is used to account for the evaporation of water from the ground and wet vegetation, along with the conversion of water to vapour through the process of transpiration by plants. Transpiration involves the transport of water (and nutrients) from roots to leaves, where it is released by evaporation to the atmosphere through stomata on leaves.

By one estimation, evapotranspiration across the global land surface (excluding water bodies and permanent ice surfaces) is 63,200 km^3yr^{-1}, which is 67% of mean annual rainfall (Zhang *et. al.* 2016), with the balance being transported back to the oceans by rivers, or diverted into deep aquifers. Transpiration by plants is responsible for recycling huge volumes of water and thus significantly contributes to atmospheric moisture, clouds and resultant rainfall. Transpiration is considered to be responsible for around 65% of evapotranspiration, evaporation from wet vegetation around 10%, and evaporation from the soil for around 25% (Zhang *et. al.* 2016). Miralles *et. al.* (2010) put the evaporation from forests as being higher, identifying that canopy interception of rainfall is responsible for the evaporation of approximately 13% of the total incoming rainfall over broadleaf evergreen forests, 19% in broadleaf deciduous forests, and 22% in needleleaf forests.

Van der Ent *et. al* (2010) consider that "*It is computed that, on average, 40% of the terrestrial precipitation originates from land evaporation and that 57% of all terrestrial evaporation returns as precipitation over land*". It has been found in the Amazon that evapotranspiration from forests accounts for more than 50% of rainfall (Nobre *et. al* 1991, Spracklen *et. al.* 2012)

The amount of water that can be recycled by evapotranspiration from vegetation is related to canopy volume (the area of leaves -Leaf Area Index) and root depth (the ability to access deeper water sources), thus it is tall forests with their large canopies and deep roots that provide the highest rate of evapotranspiration. When vegetation is cleared there is a reduction in surface area for evaporation, reduced transpiration, increased runoff and a reduced ability to access deeper soil moisture. By reducing evapotranspiration, deforestation results in less water being pumped into the atmosphere, thereby directly contributing to a decrease in rainfall (Shukla *et. al.* 1990, Nobre *et. al* 1991, Spracklen *et. al.* 2012, Andrich and Imberger 2013).

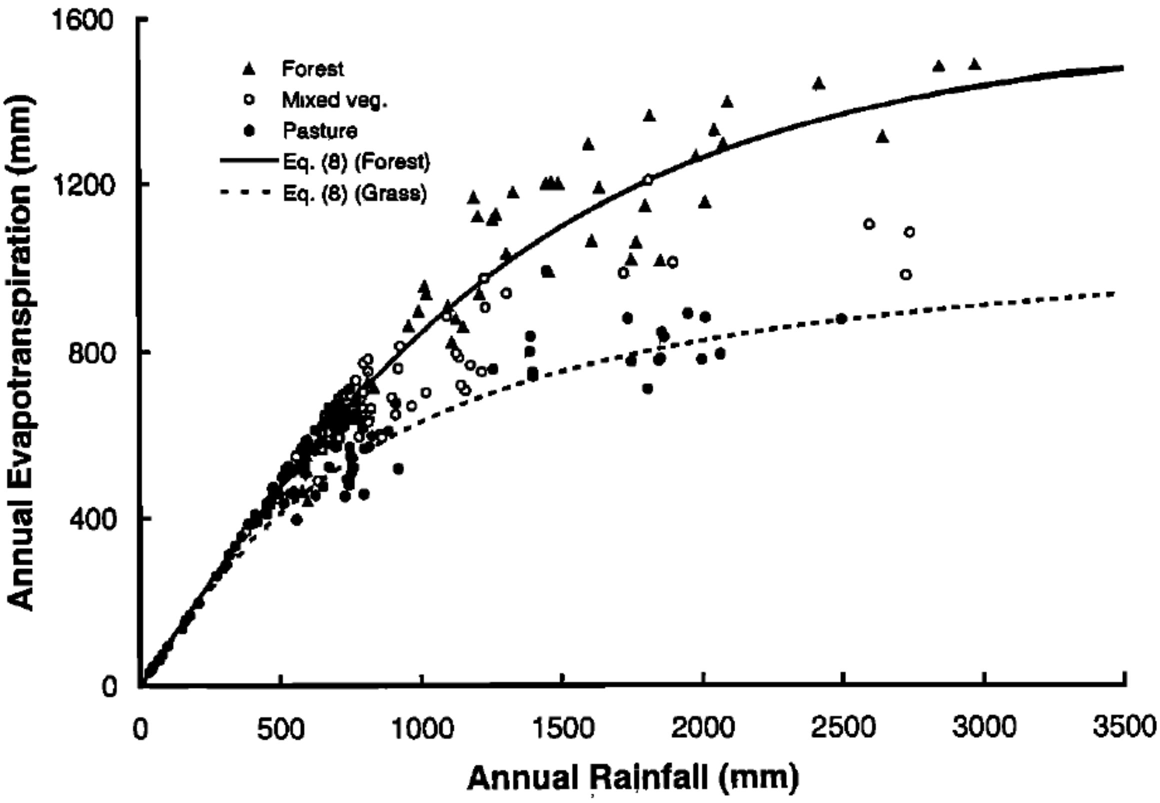


Figure 9 from Zang *et. al.* (2001): generalised relationship between annual evapotranspiration and rainfall for different vegetation types. The difference between the grass and forest curve represents the change in mean annual water yield for a 100% change in vegetation for a given mean annual rainfall.

In comparison to large canopied and deeply rooted woody vegetation, grasslands and crops only have small leaf areas and shallow rooting structures and thus lower evapotranspiration. They have less resources to tap in times of drought. Annual crops only transpire water during part of the year. They do not capture as much rainfall and soil moisture as the native vegetation, meaning less water vapour is returned to the atmosphere to be available for precipitation.

From their comparison of Amazonian pasture and rainforest, von Randow *et. al.* (2004) found that in the wet season "*evapotranspiration rates are 20% lower in the pasture, compared to the forest",* and in the dry season evapotranspiration *"rates are 41% lower in the pasture".*

Zang *et. al.* (2001) consider that "*Under dry conditions the principal controls on evapotranspiration are plant-available water and canopy resistance. Under wet conditions the dominant controls are advection, net radiation, leaf area, and turbulent transport. Under intermediate conditions the relative importance of these factors varies depending on climate, soil, and vegetation*". Zang et. al. (2001) developed a generalised model for vegetation evapotranspiration, noting "*in spite of the complexity of the soil-vegetation-atmosphere system the most important factors controlling mean annual evapotranspiration appear to be annual rainfall, potential evapotranspiration, and vegetation type*".

Most of the rain that falls upon a forest is recycled to the atmosphere through evapotranspiration, where it again becomes available for rainfall. Water may be recycled numerous times as it passes over the land before it returns to the oceans in streamflows or as rainfall. This process is vital for maintaining rainfall over inland areas.

From their analyses of tropical land surface (latitudes 30 degrees south to 30 degrees north) Spracklen *et. al.* (2012) found that for more than 60 per cent of the land air that has passed over extensive vegetation in the preceding few days produces at least twice as much rain as air that has passed over little vegetation. noting:

> *... additional moisture from evapotranspiration emitted into air masses with large exposure to vegetation is substantially greater than the additional precipitation observed in these air masses. Indeed, for all four regions the extra* [cumulative surface evaporation] *emitted into air masses with large vegetation exposure exceeds the observed additional precipitation by a factor of at least four...*
>
> *Through evapotranspiration, forests maintain atmospheric moisture that can return to land as rainfall downwind. These processes operate on timescales of days over distances of 100–1,000km ...such that large-scale land-use change may alter precipitation hundreds to thousands of kilometres from the region of vegetation change.*

In the central Amazon basin over half of the precipitated water goes back into the atmosphere through evapotranspiration, while approximately 45 percent are drained by rivers back to the ocean (Tavares 2012). Moisture-laden winds from the Atlantic Ocean account for 52 percent of the rainfall, with the balance recycled by the vegetation (Tavares 2012).

Nobre *et. al* (1991) identify that the main source of water vapour to the Amazon is the Atlantic Ocean, though in western Amazonia 2,000-3,000 km inland the water column apparently has more water vapour than near the Atlantic coast, commenting "*recycling of water vapor through evapotranspiration is clearly very important*".

Van der Ent *et. al* (2010) identify that local moisture recycling is a feature of some regions, though in most regions the majority of rainfall originates from elsewhere, for example:

> *Moisture evaporating from the Eurasian continent is responsible for 80% of China's water resources. In South America, the Río de la Plata basin depends on evaporation from the Amazon forest for 70% of its water resources. The main source of rainfall in the Congo basin is moisture evaporated over East Africa, particularly the Great Lakes region. The Congo basin in its turn is a major source of moisture for rainfall in the Sahel*.

It is important to consider that clearing forests in one region can have significant adverse impacts on rainfall in another region. Van der Ent *et. al.* (2010) consider:

> *Our results suggest that decreasing evaporation in areas where continental evaporation recycling is high (e.g., by deforestation), would enhance droughts in downwind areas where overall precipitation amounts are low. On the other hand, water conservation in these areas would have a positive multiplier effect on rainfall downwind.*

Sheil and Murdiyarso (2009) consider:

> *The world's hydrological systems are changing rapidly. Food security in many regions is heavily threatened by changing rainfall patterns (Lobell et al. 2008). Meanwhile, deforestation has already reduced vapor flows derived from forests by almost five percent (an estimated 3000 cubic kilometers [km^3] per year of a global terrestrial derived total of 67,000 km^3), with little sign of slowing (Gordon et al. 2005). The need for understanding how vegetation cover influences climate has never been more urgent.*

1.1.1. Forests as Biotic Pumps

Bernardin de Saint Pierre (1784-8) was not alone in the 18th century with his observation "*This attractive force of the forests on this island is such that a field in an uncovered situation close to them often suffers a lack of rain whereas it rains almost all year long in woods that are situated within gunshot".* It has long been observed that vegetation attracts rainfall, rather than simply being a product of it. More recent studies have confirmed such observations, though the mechanisms are still poorly understood,

It is apparent that vegetation has an ability to attract rainfall to itself even in semi-arid environments. For their study area in central Africa, Los *et. al.* (2006) identified "*positive feedback between vegetation and rainfall at the monthly time scale, and for a vegetation memory operating at the annual time scale*", noting "*These vegetation-rainfall interactions increase the interannual variation in Sahelian precipitation; accounting for as much as 30% of the variability in annual precipitation in some hot spot regions*".

In the Kalahari of southern Africa Chikoore and Jury (2010) found a flush of vegetation resulting from a rain event *"'draws' airflow toward itself in a self-sustaining way"*, noting:

> *An increase in vegetation appears to draw the airflow toward itself, enhancing the low-level buoyancy and slowing the winds through friction, thereby causing convergence and uplift. Thus vegetation seems to impact horizontal momentum transfer as much as vertical moisture flux.*

A variety of studies in tropical environments have identified that rainfall can decline following deforestation by more than the reduction in evapotranspiration can account for, indicating that there is a reduction of moisture influxes into a region following deforestation. From their observations and modelling in the Amazon, Shukla *et. al.* (1990) concluded:

> *The reduction in calculated annual precipitation by 642 mm and in evapotranspiration by 496 mm suggests that changes in the atmospheric circulation may act to further reduce the convergence of moisture flux in the region ...*
>
> *... a reduction in evaporation might be compensated for by an increase in moisture flux convergence. Our experiments indicate that such a compensation will not occur for the Amazon and that there is even a further decrease in convergence of the large-scale moisture flux.*
> *...*
> *The most significant result of this study is the simulated reduction in precipitation over Amazonia, which is larger than the corresponding regional reduction in evapotranspiration, implying that the dynamical convergence of moisture flux also decreased as a result of deforestation.*

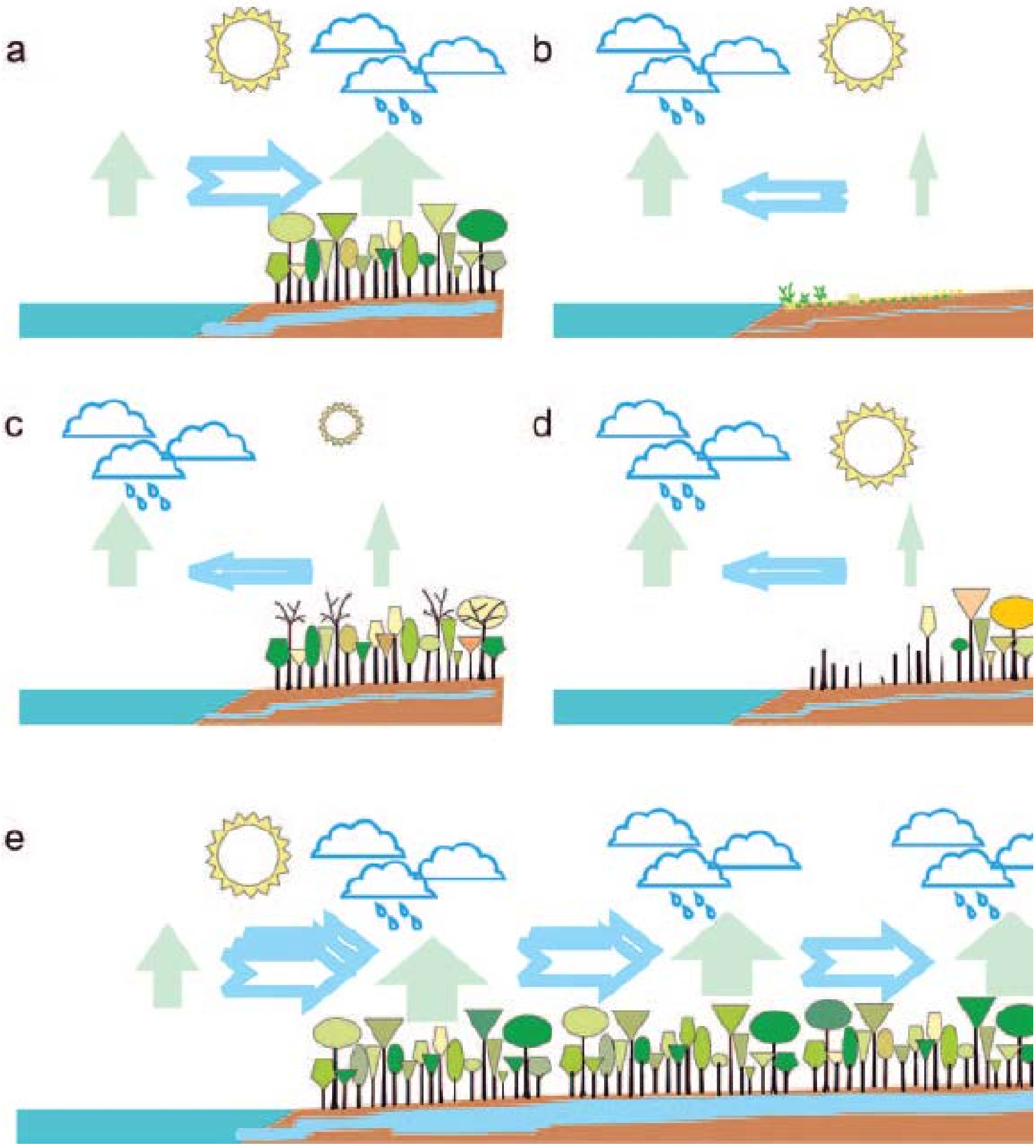
From their studies of the Amazon, Nobre *et. al* (1991) concluded "*The calculated reduction in precipitation was larger than the calculated decrease in evapotranspiration, indicating a reduction in the regional moisture convergence*".

In their modelling of the impact of conversion of savannas to grasslands, Hoffmann and Jackson (2000) found *"precipitation declined more than did evapotranspiration, indicating a reduction in moisture convergence (Table 2). Moisture convergence, that is, the net flux of water vapor into a region, has similarly been found to decline in most tropical deforestation simulations*".

It has been postulated that forests play a crucial role in hydrological cycles by acting as the Biotic Pump of atmospheric moisture (Makarieva and Gorshkov 2006, Makarieva *et. al.* 2009, Makarieva and Gorshkov 2010, Sheil and Murdiyarso 2009). From their study, Makarieva and Gorshkov (2006, 2009) concluded that the mean distance that the atmosphere can transport moisture inland over non-forested land does not exceed several hundred kilometers, with precipitation decreasing exponentially with distance from the ocean. They note that in contrast, precipitation over extensive natural forests does not depend on the distance from the ocean along several thousand kilometers.

Makarieva and Gorshkov (2006) found that areas with strong evaporation/transpiration draw in moisture from areas with low evaporation, thereby enhancing rainfall. Makarieva and Gorshkov (2006) postulated that natural forests are the biotic pump of atmospheric moisture:

> *Due to the high leaf area index, natural forests maintain powerful transpiration exceeding evaporation from the oceanic surface. The transpiration flux supports ascending fluxes of air and “sucks in” moist air from the ocean. In the result, forest precipitation increases up to a level when the runoff losses from optimally moistened soil are fully compensated at any distance from the ocean.*
>
> *Natural forest ecosystems, with their high leaf area index and high transpiration exceeding evaporation from open water surface, are capable of pumping atmospheric moisture from the ocean in amounts sufficient for the maintenance of optimal soil moisture stores, compensating the river runoff and ensuring maximum ecosystem productivity.*



An illustration of the biotic pump, from Sheil and Murdiyarso (2009): Atmospheric volume reduces at a higher rate over areas with more intensive evaporation solid vertical arrows, widths denotes relative flux). The resulting low pressure draws in additional moist air (open horizontal arrows) from areas with weaker evaporation. This leads to a net transfer of atmospheric moisture to the areas with the highest evaporation. (a) Under full sunshine, forests maintain higher evaporation than oceans and thus draw in moist ocean air. (b) In deserts, evaporation is low and air is drawn toward the oceans. (c) In seasonal climates, solar energy may be insufficient to maintain forest evaporation at rates higher than those over the oceans during a winter dry season, and the oceans draw air from the land. However, in summer, high forest evaporation rates are re-established (as in panel a). (d) With forest loss, the net evaporation over the land declines and may be insufficient to counterbalance that from the ocean: air will flow seaward and the land becomes arid and unable to sustain forests. (e) In wet continents, continuous forest cover maintaining high evaporation allows large amounts of moist air to be drawn in from the coast. Not shown in diagrams: dry air returns at higher altitudes, from wetter to drier regions, to complete the cycle, and internal recycling of rain contributes significantly to continental scale rainfall patterns. Source: Adapted from ideas presented in Makarieva and Gorshkov (2007).

A review of the Biotic Pump theory by Sheil and Murdiyarso (2009) concluded:

> *The underlying mechanism emphasizes the role of evaporation and condensation in generating atmospheric pressure differences, and accounts for several phenomena neglected by existing models. It suggests that even localized forest loss can sometimes flip a wet continent to arid conditions. If it survives scrutiny, this hypothesis will transform how we view forest loss, climate change, hydrology, and environmental services. It offers new lines of investigation in macroecology and landscape ecology, hydrology, forest restoration, and paleoclimates. It also provides a compelling new motivation for forest conservation.*
>
> *...*
>
> *Researchers have previously puzzled over a missing mechanism to account for observed precipitation patterns (Eltahir 1998). Makarieva and Gorshkov's hypothesis offers an elegant solution: they call it a "pump."*
>
> *...*
>
> *Conventional models typically predict a "moderate" 20 to 30 percent decline in rainfall after continental-scale deforestation (Bonan 2008). In contrast, Makarieva and Gorshkov suggest that even relatively localized clearing might ultimately switch entire continental climates from wet to arid, with rainfall declining by more than 95 percent in the interior.*

For the biotic pump to provide more inland rainfall, vegetation transpiration fluxes need to exceed the fluxes of evaporation from the open water surface of the ocean. The strength and effectiveness of the biotic pump, and thus inland rainfall, is dependent on the number of trees in the forest and the area of the forest-cover. Makarieva and Gorshkov (2006) found that "*Replacement of the natural forest cover by a low leaf index vegetation leads to an up to tenfold reduction in mean continental precipitation and runoff*", also noting:

> *The biotic moisture pump, as well as the mechanisms of efficient soil moisture preservation ... work in undisturbed natural forests only. Natural forest represents a contiguous cover of tall trees that are rigidly associated with other biological species of the ecological community and genetically programmed to function in the particular geographic region. The vegetation cover of grasslands, shrublands, savannas, steppes, prairies, artificially thinned exploited forests, plantations, pastures or arable lands is unable to switch on the biotic moisture pump and maintain soil moisture content in a state optimal for life. Water cycle on such territories is critically dependent on the distance from the ocean; it is determined by random fluctuations and seasonal changes of rainfall brought from the ocean. Such territories are prone to droughts, floods and fires.*
>
> *... If the natural forest cover is eliminated along the oceanic coastline on a band* [around] *600 km wide, the biotic moisture pump stalls. The remaining inland forests are no longer able to pump atmospheric moisture from the ocean. There is no longer surplus to runoff to rivers or to recharge groundwater. ...*
>
> *...*
>
> *The results obtained form the basis of a possible strategy to restore human-friendly water conditions on most part of the Earth's landmasses, including modern deserts and other arid zones. As we have shown, elimination of the forest cover in world's largest river basins would have the following consequences: at least one order of magnitude's decline of the river runoff, appearance of droughts, floods and fires, partial desertification of the coastal zone and complete desertification of the inner parts of the continents, ...associated economic losses would by far exceed the economic benefits of forest cutting ... Therefore, it is worthy to urgently reconsider the modern forest policy everywhere in the world. First of all, it is*

> *necessary to immediately stop any attempts of destroying the extant natural forest remnants and, in particular, those bordering with the ocean or inner seas. Further on, it is necessary to initiate a world-wide company on facilitating natural gradual recovery of aboriginal forest ecosystems on territories adjacent to the remaining natural forests. Only extensive contiguous natural forests will be able to run a stable water cycle and subsequently intensify it, gradually extending the river basin at the expense of newly recovering territories.*

Makarieva and Gorshkov (2006) conclude:

> *Forests are responsible both for the initial accumulation of water on continents in the geological past and for the stable maintenance of the accumulated water stores in the subsequent periods of life existence on land. ... It is shown that only intact contiguous cover of natural forests having extensive borders with large water bodies (sea, ocean) is able to keep land moistened up to an optimal for life level everywhere on land, no matter how far from the ocean.*

1.2. Energy Fluxes

Incoming solar energy (shortwave radiation) can be reflected back into space (mostly off clouds or by the earth's surface) or absorbed in the atmosphere (mainly by oxygen, ozone and water vapour). The fraction of solar energy that is reflected is determined by the surface albedo, which depends on the optical properties of the surface.

Around half the incoming solar energy is absorbed by the earth's surface, vegetation and waters. The solar energy can either heat the surface and raise its temperature (sensible heating) or it can change the phase of water from liquid to vapour (evaporate) without a corresponding temperature change (latent heating). Latent refers to the heat which "disappears" without causing a temperature change.

A large portion of this surface energy transported back into the atmosphere as “radiative” fluxes and “turbulent” fluxes. The turbulent fluxes are associated with wind replenishing air at the surface-atmosphere interface; turbulent sensible heat-fluxes (associated with convection) are driven by the difference in temperatures between the surface and the atmosphere, and turbulent latent heat fluxes (e.g. evaporation) are driven by difference in vapour pressure between surface and atmosphere.

The atmosphere is heated by heat emitted from sunlight-warmed surfaces and heat released by condensation of water vapour, and cooled by radiation re-emitted both upwards and downwards. Water vapour is nearly opaque at the long wavelengths at which the surface radiates away its absorbed energy. The absorption of most of the outgoing thermal radiation by water vapour creates most of Earth's natural greenhouse effect. By reducing heat losses from the earth's surface, atmospheric gases and aerosols keep the earth around 33°C warmer than it otherwise would be. Atmospheric water vapour is the dominant contributor to the greenhouse effect, contributing up to 60% of the total radiative forcing compared to carbon dioxide's 26% (Kiehl and Trenberth 1997).

Rainfall occurs because as air heats it takes up more water vapour and begins to rise, as it rises it cools (by roughly one degree centigrade for every 100m of altitude in dry air), as the air cools cloud droplets begin to form around aerosols such as dust, sea salt, bits of organic matter, or chemical aerosol particles, as the water condenses its stored heat is released.

Water has a high capacity for the storing and transporting of heat and so is able to redistribute much of the solar heat energy through the water cycle. By its regulation of evapotranspiration and condensation vegetation has a profound influence on the water cycle, and thus plays a key role in earth's energy budget.

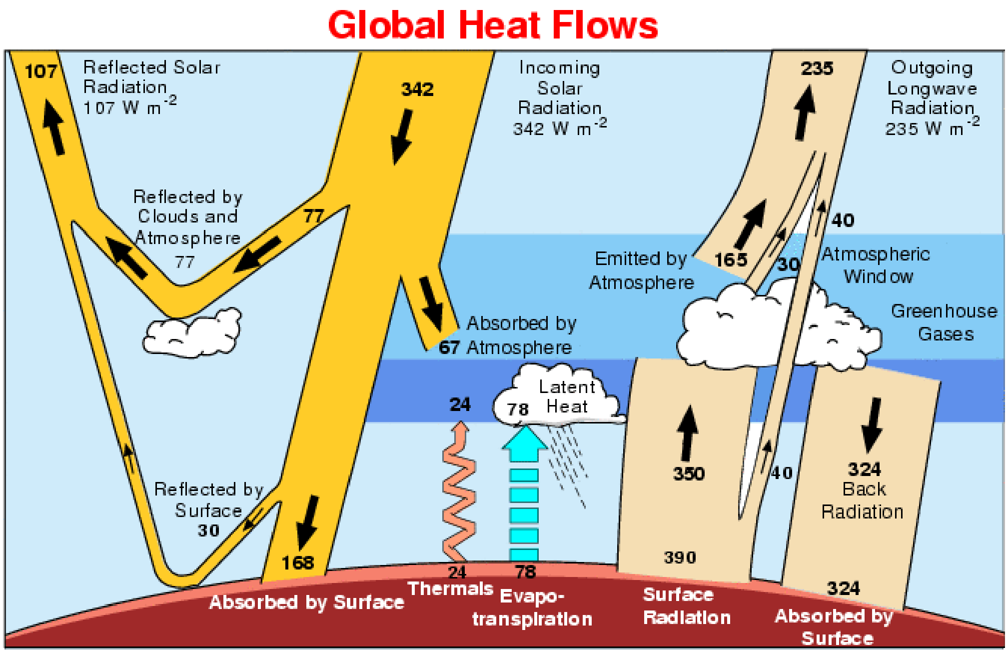


Figure 7, adapted from Kiehl and Trenberth (1997) The earth's annual global mean energy budget based on the present study. Units are W m□2.

When vegetation is cleared, the direct feedbacks include alterations of absorbed solar radiation due to albedo changes, and perturbations to the partitioning of net radiation between sensible, latent and ground heat.

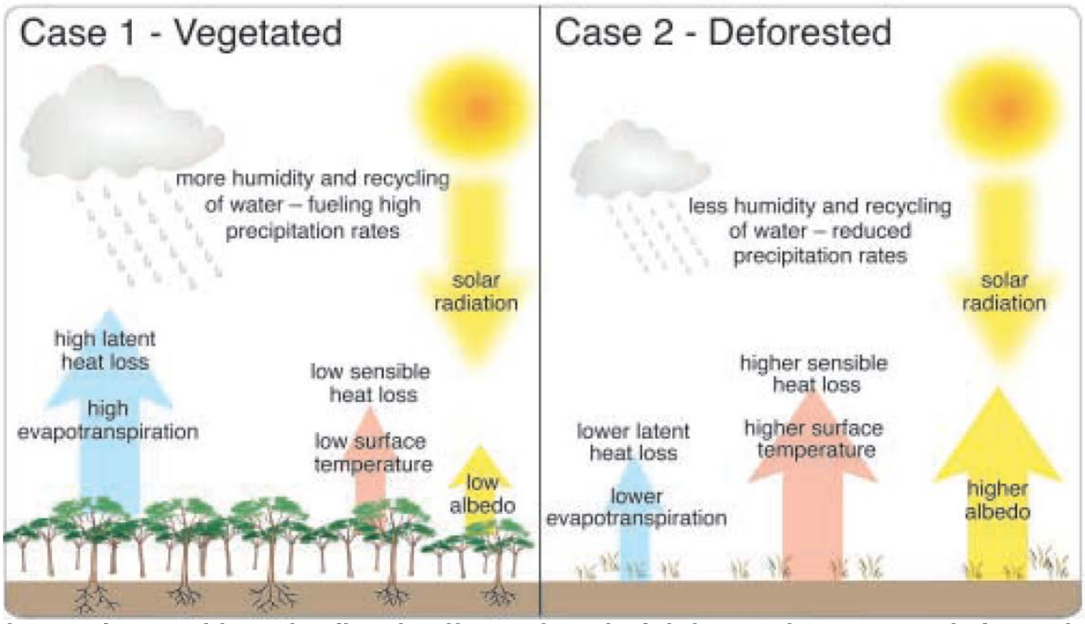


Figure 2 from Foley *et. al.*(2002): Climatic effects of tropical deforestation on water balance, boundary layer fluxes, and climate. In vegetation-covered areas (left), the low albedo of the forest canopy provides ample energy for the plants to photosynthesize and transpire, leading to a high latent heat

loss that cools the surface. In deforested areas (right), bare soil's higher albedo reduces the amount of energy absorbed at the surface. Latent heat loss is severely reduced and the surface warms, as it has no means of removing the excess energy through transpiration.

1.2.1. Albedo

The amount of solar energy reflected back into space by a surface is referred to as its albedo. Albedo is the percentage of radiation the surface reflects. Changes in surface albedo due to deforestation has been considered by some researchers to be one of the main drivers of climate responses.

One effect of deforestation is the change in surface albedo. If the resulting surface is lighter coloured and more reflectent, more incoming solar energy is reflected, cooling the surface. If the surface is darker more energy is absorbed. White surfaces, such as snow and ice, have a high albedo (60-90% of solar energy reflected), sand has a moderate albedo (30-45%), bare soil a variable albedo (5-40%, depending on wetness and soil colour) and vegetation a low albedo: forests (8-20%), agricultural crops (18-25%) and grasslands (16-26%). Depending on their density, clouds also have a high albedo (30-90%).

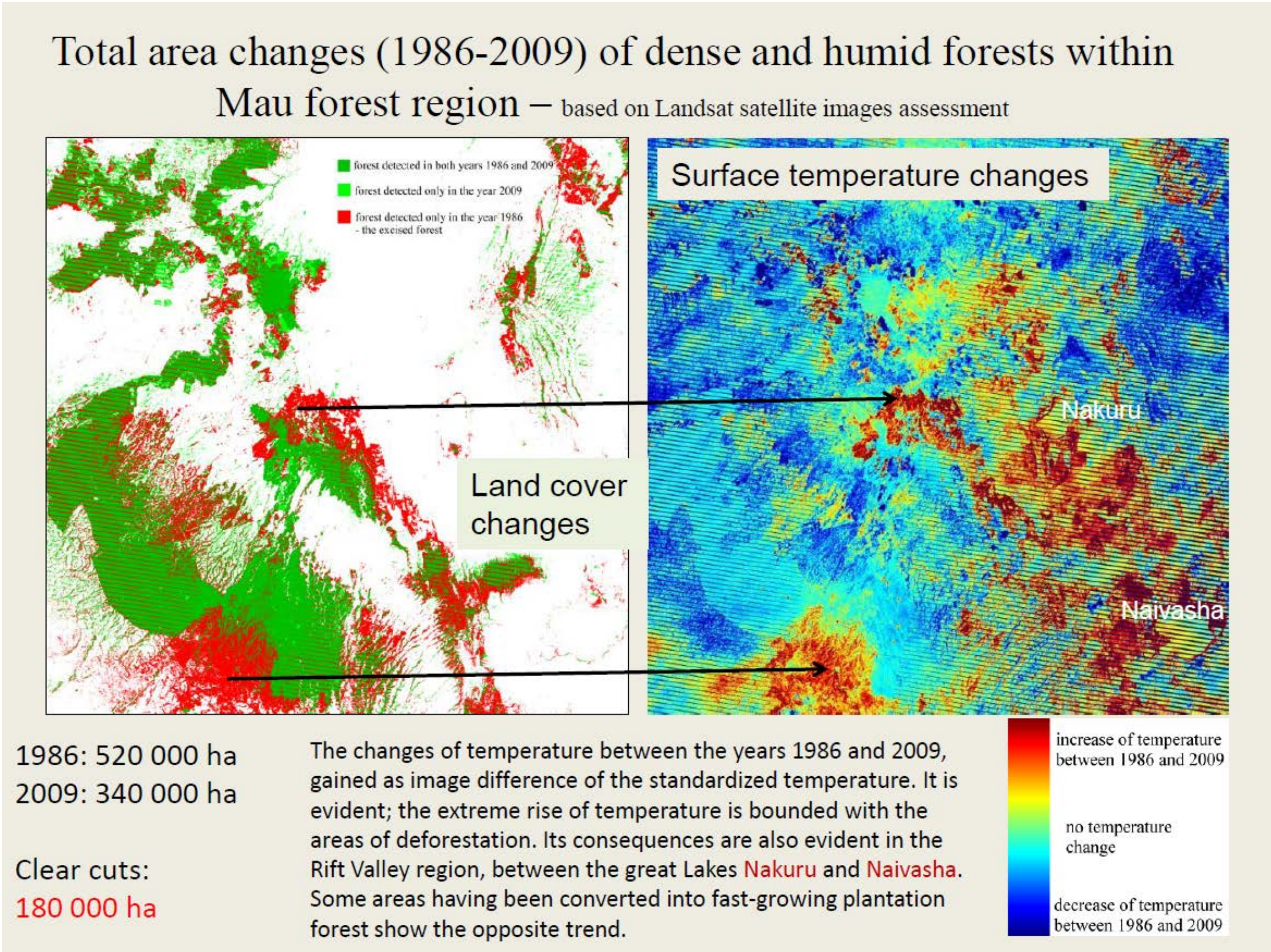
In temperate areas the increase in albedo resulting from deforestation is generally considered to have a cooling climatic effect, this is because grasses, crops and bare soils can have a higher albedo, though the primary response is considered to relate to the removal of canopy over snow increasing albedo and the feedback of reduced temperatures extending snow cover. In tropical areas the albedo effect is considered to be offset by the loss of the evaporative cooling effect of the removed vegetation and the reduction in cloud cover with its high albedo, resulting in a warming effect. (i.e. Sud and Smith 1985, Meher-Homji 1991, Nobre *et. al* 1991, Claussen 1998, Sud *et. al.* 1998,, Giambelluca *et. al*. 1999, Hoffmann and Jackson 2000, Brovkin 2002, Foley *et. al.* 2003b, von Randow *et. al.* 2004, Brovkin. *et. al.* 2006, Findell *et. al.* 2007, Findell *et. al.* 2009, Lawrence and Chase 2010, Davin and de Noblet-Ducoudré 2010, Deo 2011, Pitman *et. al.* 2012, Chen and Dirmeyer 2016).

Though the increase in albedo, and thus reduced temperatures, resulting from deforestation has been questioned (Eiseltová *et. al.* 2012, Chen and Dirmeyer 2016). From their comparisons of thermal satellite images in Europe and Africa Eiseltová *et. al.* (2012) identified significant increases in ground temperatures from deforestation, noting that in Kenya deforestation from 1986-2009 resulted in "*Extreme rises in temperature (by more than 20° C ...)*", and concluding "*Sites with bare ground undoubtedly belong to the warmest places in the landscape; due to the lack of water evapotranspiration, more solar energy is transformed into sensible heat (raising the site's temperature) than into latent heat of water vapour. The higher albedo of bare ground (concrete, etc.) and the lower albedo of forests does not play such an important role when compared to the cooling effect of evapotranspiration*".

In the Amazon, von Randow *et. al.* (2004) found that pasture had a significantly higher albedo than rainforest, noting "*For the radiation balance, the reflected short wave radiation increases by about 55% when changing from forest to pasture. Combined with an increase of 4.7% in long wave radiation loss, this causes an average reduction of 13.3% in net radiation in the pasture, compared to the forest*", and "*long-wave balance was a more important determinant of seasonal variations of the net radiation, than the albedo*".

Also contrary to accepted wisdom, from their study Luyssaert *et al*. (2014) observed that an increase in albedo was related to an increase in surface temperature, commenting it "*may seem paradoxical if less energy is available for surface heating following an increase in albedo*". Further investigations confirmed their opinion, "*Across all paired observations, the potential for cooling the surface due to an increase in albedo ... was outweighed by the potential for warming due to decreased fluxes of sensible heat ... but not latent heat ... For the sites under study, sensible heat and changes in sensible heat thus seem to be key drivers of the surface temperature and its changes following* [Land Cover Change] *or* [Land Management Change]". They conclude:

> *our study reveals that changes in sensible heat flux outweigh changes in albedo and underlie surface temperature changes in the temperate zone following both LCC and LMC.*



Based on comparisons of surface temperature change from forest to open land at paired observation sites, Chen and Dirmeyer (2016) identified that in summer deforestation leads to an observed daytime warming (+2.23±0.94 K) and a cooling effect at night (−2.05±1.02 K), with albedo only having a minor effect:

> *The radiation term has a slight cooling effect during day (−0.08±0.07 K), attributable to albedo change cooling being nearly offset by more infrared radiation from the warmer surface. Ground heat flux shows a warming effect during nighttime (0.18±0.12 K).*

From their modelling Lawrence and Chase (2010) identified that clearing of native vegetation results in "*year round warming of the near surface atmosphere in tropical and subtropical regions, and the winter cooling and summer warming in higher northern latitudes*".

In relation to tropical deforestation Foley et. al. (2003b) note:

> *First, the increase in albedo tends to cool the surface, by reducing the amount of solar radiation it can absorb. However, surface roughness, leaf area, and root depth are lower in pastures than in forests; this dramatically reduces evapotranspiration from the smoother surface, which in turn substantially increases its temperature. As a result, the cooling effect of the higher albedo is completely offset, and often surpassed, by the reduction in evaporative cooling. The net effect is a warming of approximately 1–2 °C in tropical regions undergoing large-scale deforestation*

Deo (2011) considers:

> *A higher surface albedo should result in a cooler surface because less radiation is absorbed. However, since modified landscapes (e.g. farming areas) have lower vegetation fraction, leaf-area index and rooting depths, this dramatically reduces evapotranspiration rates relative to native forests. As a result of reduction in evaporative cooling, less heat escapes from the land surface causing an increase in mean surface temperatures*
>
> *Changes in surface albedo can also contribute to changes in mean rainfall. The increase in surface albedo for modified land-cover conditions could produce a drier lower atmosphere, suppressing the formation of convective clouds and raindrops*

Hoffmann and Jackson (2000) note that an increase in albedo can reduce convection by reducing heat flux into the lower atmosphere. In their simulation of Monsoon rainfalls over India, Sud and Smith (1985) found the influence of increasing albedo "*was to reduce rainfall over India*". For south-east Queensland Cottrill (2009) found "*albedo affected rainfall in this region, with higher albedo leading to lower rainfall over pastoral and agricultural regions west of the Great Dividing Range*".

1.2.2. Redistributing Solar Energy

Conversion of solar energy absorbed by the earth's surface into latent heat (without a rise in temperature) by evaporation is an integral part of the climate system, linking the surface energy balance to the hydrological cycle. When water changes from a liquid to its gaseous phase energy is stored in the water vapour in the form of latent heat and produces evaporative cooling. Water vapour fluxes transport latent heat from the location where water evaporates to where the water condenses, often in clouds. The increase in clouds associated with increased evaporation increases reflection of solar radiation and thereby causes a surface cooling.

The conversion of liquid water into vapour by transpiration has been estimated to require roughly half of all solar energy absorbed by the continents (Jasechko *et. al.* 2013). Evapotranspiration thus has a cooling effect on climate, which is reinforced by the formation of clouds with their higher albedo.

Because of their deep roots, deep canopies and large leaf areas, forests are the most effective vegetation at maximising evapotranspiration, giving forests a greater latent heat flux relative to sensible heat flux than grasslands or crops.

The partitioning between ecosystem latent and sensible heat fluxes is critical in determining the hydrological cycle, boundary layer development, weather and climate (Wilson *et al.* 2002).

Deforestation results in a net decrease in evapotranspiration and thus latent heat, making more energy available for sensible heat flux and increasing the surface temperature. The reduced transpiration decreases atmospheric moisture and cloud cover. The increase in sensible heat means more longwave radiation leaving the earth's surface and, because of the reduced low cloud cover, less of this radiation is returned to the surface. The reduced cloud cover means more shortwave radiation can reach the earth's surface.

By reducing evapotranspiration, deforestation tends to cause an increase in sensible heat and surface temperatures (Shukla *et. al.* 1990, Pielke 2001, Foley *et. al.* 2003b, von Randow *et. al.* 2004, Findell *et. al.* 2007, Findell *et. al.* 2009, Lawrence and Chase 2010, Davin and de Noblet-Ducoudré 2010, Kovářová *et. al.* 2011, Deo 2011, Lee *et. al.* 2011, Bagley 2011, Ban-Weiss *et. al.* 2011, Pitman *et. al.* 2012, Eiseltová *et. al.* 2012). Kovářová *et. al.* (2011) found "*The air temperature increases at areas where a decline of available water occurs and latent heat of evapotranspiration shifts to sensible heat*". Pielke 2001 consider "*Once the surface energy budget is altered, fluxes of heat, moisture, and momentum within the planetary boundary layer are directly affected"*.

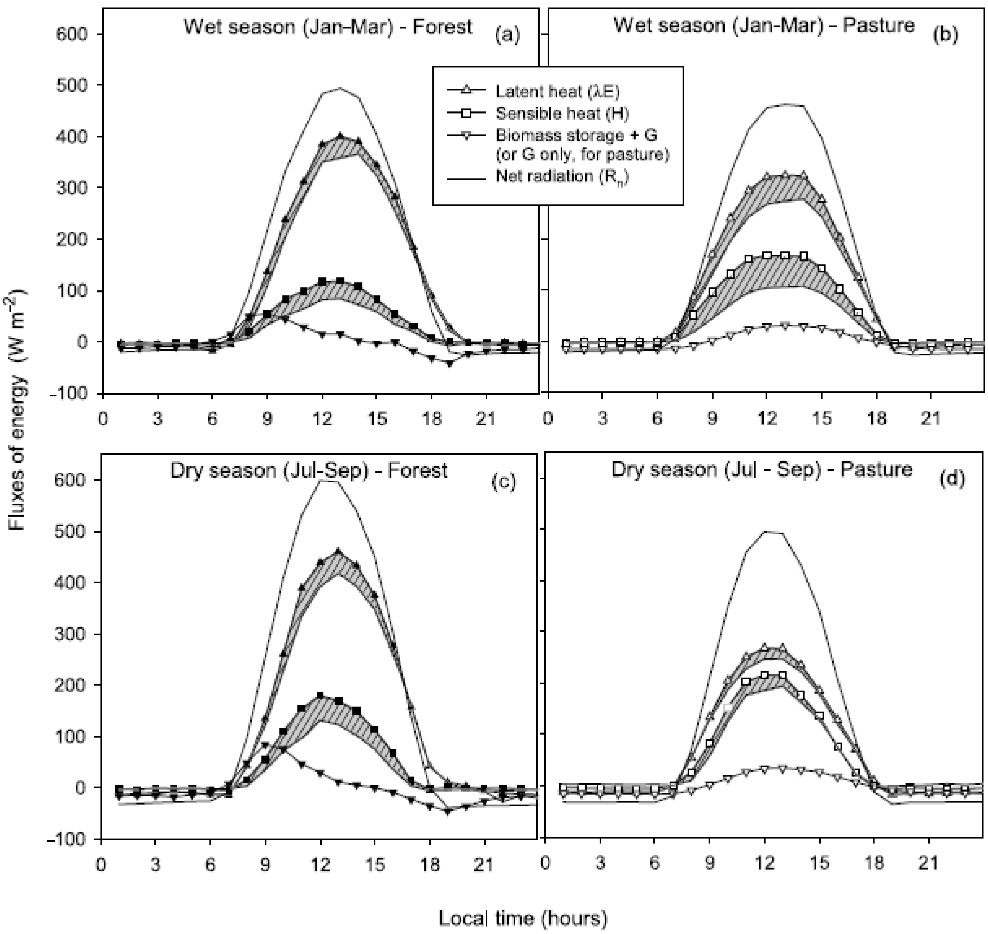


Fig. 9. from Von Randow *et. al.* (2004): Average daily patterns of net radiation (Rn), sensible and latent heat fluxes (H and \E respectively) and soil heat fluxes (+ heat storage in canopy at forest), for: (a) wet season at forest; (b) wet season at pasture; (c) dry season at forest and (d) dry season at pasture. Dashed areas represent the ranges of heat fluxes calculated using two different procedures.

Von Randow *et. al.* (2004) undertook comparisons of energy fluxes in Amazonian pasture and rainforest, finding:

> *The radiation flux components are markedly different between the two sites. The most important changes occur in the reflected short wave radiation, which increases about 55% when changing from forest to pasture. Combined with an increase of 4.7% on long wave*

radiation loss, this causes an average reduction of 13.3% in the net radiation in the pasture, compared to the forest....

Large differences between the two types of surface are also noticed in the energy partition between sensible and latent heat fluxes. In the wet season the sensible heat fluxes are 45% higher, while the evapotranspiration rates are 20% lower in the pasture, compared to the forest. In the dry season, the differences are lower in the sensible heat (fluxes are 28% higher in the pasture), while the changes in evapotranspiration are large (rates are 41% lower in the pasture).

From their modelling of the effect of land-clearing on heat fluxes, Ban-Weiss *et. al.* (2011) identifies that historical deforestation has reduced the latent heat flux on land on the order of half a watt per meter square (W m^{-2}) averaged over all land, with changes up to about 20 W m^{-2} for specific locations and seasons, noting "*studies suggest that a reduction in latent heat increases local surface temperatures due to the loss of evaporative cooling*".

However they consider that " *On the global scale, changes in surface evaporative cooling are largely compensated by changes in condensation of the water vapor in the atmosphere ... Thus, changes in latent heating do not directly affect the global energy balance. Therefore, global temperature changes are caused by changes in atmospheric properties such as water vapor content, clouds and the vertical temperature profile*". Finding that "*When increasing upward latent heat fluxes while decreasing sensible heat fluxes, there is an increase in low clouds associated with increased evaporation. The increased reflection of downward solar radiation from these clouds is the dominant factor driving the global cooling found here*".

Eiseltová *et. al.* (2012) consider:

In landscapes with water - abundant aquatic ecosystems, wetlands and soils with high water retention capacity - about 80 % of incoming solar energy is stored as latent heat of water vapour via evapotranspiration, whilst in de-watered landscapes (with a low-water retention capacity) the vast majority of solar energy is transformed into sensible heat.

Deo (2011) considers:

The principle of energy conservation requires that the decrease in evaporative cooling (latent heat) be compensated by an increase in convective heating (sensible heat), assuming ground heat flux is negligible. As such, there is a substantial change in partitioning of available solar energy at the land surface from latent heat to sensible heat flux due to deforestation. Deo et al. (2009) showed that summer-averaged latent heat flux decreased by ~4.8Wm^{-2} while sensible heat increased by ~1.1Wm^{-2} as the surface was modified from a pre-European (native vegetation) to modern day (modified) state. The large reduction in evaporative cooling is consistent with a warmer land surface for modified land cover conditions contributing to a reduction in mean rainfall.

Lawrence and Chase (2010) consider:

... warming was predominantly in response to reduced evapotranspiration and therefore latent heat flux in the current day experiment, with radiative forcing playing a secondary role. The idea that replacing forests with grass and crop lands results in regional warming through reduced evapo-transpiration is not new.

Models can have completely opposite changes in surface temperature and latent heat flux associated with deforestation, which could be due to problems with some models (i.e. Lawrence and Chase 2010, de Noblet-Ducoudré *et. al.* 2012). Ban-Weiss *et. al.* (2011) caution:

> *In studies of 'realistic' land use and land cover change, it is often difficult to identify what component of climate change may be attributed to changes in latent and sensible heating. Real changes in surface properties would also affect surface albedo and roughness, and it is generally difficult to partition predicted climate change among these causes.*

Pitman *et. al.* (2012) found that many of the temperature indices show locally strong and statistically significant responses to deforestation, noting "*commonly 30–50% of the continental surfaces of the tropics and Northern and Southern Hemispheres are affected statistically significantly*".

From their experiments with 7 coupled atmospheric models de Noblet-Ducoudré *et. al.* (2012) found "*that there is no consistency among the various models regarding how* [land use-land cover change] *affects the partitioning of available energy between latent and sensible heat fluxes at a specific time*". Though for Eurasia and North America de Noblet-Ducoudré *et. al.* (2012) found that "*all models that undergo a change in their forest fraction that is larger than 15% simulate cooler ambient air temperature in all seasons*".

From his modelling of Land Cover Change (LCC) Deo (2011) considered:

> *Such a large shift in energy flux from evaporative cooling to convective heating demonstrates that LCC can exacerbate climate anomalies, such as El Niño events.*
> *...*
> *Since the conversion of native forests into cropping and grazing pastures contribute to an increase in sensible heating, a warmer atmosphere can lead to an increase in the number of hot days. Conversely, the decrease in latent (or evaporative) heating can offset the amount of moisture available for the formation of rain through a reduction in evaporation and transpiration rates. This can produce an increase in the number of dry days. Increases in the number of dry days and more intense heating of the lower atmosphere can lead to more extreme conditions such as droughts and heatwaves ...*
>
> *Second, the reduction in surface roughness, leaf area, and root depth dramatically limits how much water vapor can be recycled into the atmosphere locally through evapotranspiration – an important component of the hydrologic cycle of tropical rainforests ...*

Lawrence and Chase (2010) warn:

> *The robust decreases in evapo-transpiration and regional warming found in the CCSM experiments, and in the supporting field observations and modeling studies, have implications for future land use and the regional impacts of climate change under enhanced atmospheric greenhouse gas concentrations. As the land surface and the hydrological cycle continue to be modified through deforestation, urbanization, agricultural development, further reductions in evapo-transpiration may substantially enhance regional warming on top of projected global warming.*

1.3. Surface Roughness

The structure of vegetation has a significant impact on rainfall that is related to its height, leaf area density, and canopy roughness. Natural vegetation reduces wind speed through its aerodynamically rough, undulating canopy, causing turbulence and the mixing of air. Due to the decrease in wind velocity, the air masses are forced to stack and rise, which is enhanced by the height of the vegetation. This increases the influx of water vapour into the lower atmosphere, and thus promotes condensation and rainfall. As described by Bagley (2011):

> *Depending on whether surface roughness increases or decreases the change enhances or diminishes fluxes of water, energy, and momentum from the earth's surface to the atmospheric boundary layer through the enhancement or diminishment of eddy formation in the surface layer*

Just by their height trees can have an orographic effect (moist air rising over a physical barrier), as noted by Andrich and Imberger (2013) for Western Australia: "*Rainfall changes by ~40 mm for every 100 m in altitude between Fremantle and the hill reservoirs*". Cutting down trees thus reduces the "*surface boundary layer height*" and rainfall.

The decrease in surface roughness caused by deforestation reduces the transfer of energy to the atmosphere in the form of turbulent fluxes and thus rainfall. The low and even canopies of crops and grasslands reduce surface roughness, turbulent mixing in the boundary layer, evapotranspiration and thus rainfall. This is considered by many researchers to be a key contribution to the decrease in rainfall resultant from land cover change (Sud and Smith 1985, Shukla *et. al.* 1990, Nobre *et. al* 1991, Meher-Homji 1991, Claussen 1998, Sud *et. al.* 1998, Hoffmann and Jackson 2000, Foley *et. al.* 2003b, Pitman *et.al.* 2004, Sheil and Murdiyarso 2009, Findell *et. al.* 2007, Chapin III *et al*., 2008, Sheil and Murdiyarso 2009, Findell *et. al.* 2009, McAlpine *et. al.* 2009, Davin and de Noblet-Ducoudré 2010, Nair *et. al* 2011, Kala *et. al.* 2011, Deo 2011, Bagley 2011, de Noblet-Ducoudré *et. al.* 2012, Andrich and Imberger 2013, Chen and Dirmeyer 2016).

Sheil and Murdiyarso (2009) state:

> *Forest evaporation benefits from canopy height and roughness, which leads to turbulent airflows. This has been termed the "clothesline effect," as it is the same reason laundry dries more quickly on a line than when laid flat on the ground (Calder 2005). If moisture is sufficient, forest evaporation is constrained principally by solar radiation and weather (Calder et al. 1986, Savenije 2004). Large tropical trees can transpire several hundred litres of water each day (Goldstein et al.1998).*

An example of the aerodynamic effect on local precipitation has been studied in south-west Australia, where rainfall has reduced and river flows around the city of Perth have fallen by around 40% since the mid twentieth century. This decreasing trend has been attributed to deforestation (Adams 2010). The replacement of forests by cropland and pasture has reduced the aerodynamic roughness of the surface. After clearance of the forests, the rainfall occurs further inland and outside of the river catchments around Perth. An analysis of observations and regional model results by Nair et al. (2011) supports these ideas. The loss of the forest has resulted in reduced wintertime rainfall over the areas cleared, which is partly caused by the reduced aerodynamic roughness after conversion of forests to crops. A more heterogeneous pattern of forest and wheat could have helped to reduce the local change in rainfall (Chapin III *et al*., 2008).

Kala *et. al.* (2011) modelled a summer and a winter cold front in south-west WA to assess the impacts of land clearing, and:

> *found that land-cover change results in a decrease in precipitation for both fronts, with a higher decrease for the summer front. The decrease in precipitation is attributed to a decrease in turbulent kinetic energy and moisture flux convergence as well as a increase in*

> *wind speed within the lower boundary layer. The suggested mechanism is that the enhanced vertical mixing under pre-European vegetation cover, with the decrease in wind speeds close to the ground, enhance microphysical processes leading to increased convective precipitation. The higher decrease in precipitation for the summer front is most likely due to enhanced convection during summer.*

From their modelling of Monsoon rains over India, Sud and Smith (1985) concluded that "*the influence of surface roughness change is as important as that of surface albedo change*", identifying that "*small changes in wind magnitude or direction, can produce significant changes in the moisture convergence and rainfall*", and that "*the presence of tall vegetation over India would increase its July rainfall*". From their global modelling review, Sud *et. al.* (1998) considered that they showed "*that the surface roughness significantly influences the atmospheric circulation and precipitation, especially in the tropics, because it directly affects the boundary layer water vapor transport convergence*", concluding that the *"height of the earth's vegetation cover, which is the main determinant of surface roughness, has a large influence on the boundary layer water vapor transport convergence and the rainfall distribution*".

As well as decreasing rainfall, the reduction in surface roughness due to deforestation is considered to have a strong warming influence (Foley *et al*. 2003, Davin and de Noblet-Ducoudré 2010, Deo 2011, Chen and Dirmeyer 2016), Davin and de Noblet-Ducoudré (2010) noting "*reduced surface roughness leads to weaker turbulent exchanges. Since the energy available at the surface cannot be transferred to the atmosphere through turbulent fluxes, the surface tends to warm*"

Chen and Dirmeyer (2016) consider that surface roughness effects usually dominate the direct biogeophysical feedback of deforestation, while other effects play a secondary role, finding:.

> *Grasslands or croplands are aerodynamically smoother than forest and transfer heat less effectively, thus experiencing higher surface temperatures during daytime and lower surface temperatures at night*

Based on comparisons of surface temperature change from forest to open land at paired observation sites, Chen and Dirmeyer (2016) identified that in summer deforestation leads to an observed daytime warming (+2.23±0.94 K) and a cooling effect at night (−2.05±1.02 K), noting "*roughness change exhibits the largest impact (1.96+0.60 K during the day, −1.62+0.61 K at night)*".

Vegetation can also directly strip water from fog and clouds in mountainous areas and along coastal fog zones with significant affects on the water available for the forests, transpiration and streamflows (i.e. Lima 1984, Meher-Homji 1991, Hutley *et. al.* 1997, Foley et. al. 2003b, Sheil and Murdiyarso 2009). Meher-Homji (1991) note:

> *Even a single tree or a group of trees can trap a substantial quantity of rainwater through the process called horizontal precipitation .... The amount so trapped can vary from 7 to 18% of the rainy-season precipitation and up to 100% of dry-season rains .... The destruction of such cloud forests (as in the Western Ghats of India) can diminish stream flows and ground-water recharge.*

Hutley *et. al.* (1997) identify that numerous observers have considered that the occurrence of low cloud, fog and mist may be important to the survival of Australian rainforests at upland sites. They assessed a rainforest site on the Great Dividing Range west of Brisbane, finding that leaves were wet for 25% of the time solely from dew and fog events, with frequent wetting of the canopy reducing transpiration rates, and allowing the leaves to directly absorb liquid surface water. Hutley *et. al.* (1997) conclude:

> *Fog deposition to the forest provides the equivalent of an additional 40% of rainfall to the site as measured using a conventional rain gauge. A frequently wet canopy results in reduced transpiration rates and direct foliar absorption of moisture alleviates water deficits of the upper crown leaves and branches during the dry season. These features of this vegetation type may enable long-term survival at what could be considered to be a marginal rainforest site.*
>
> *...*
>
> *Near-coastal massifs, such as the Great Dividing Range in southern Queensland, will have an ability to intercept and deflect moist air, which will have a significant local impact on rainfall. The present study has demonstrated the importance of fog and cloud occurrence. This could also be true of upland sites along the entire Eastern Highlands of Australia and may be significant given the frequency of the occurrence of water deficits in Australian rainforests.*

1.4. Aerosols

Aerosols are minute particles suspended in the atmosphere, some of which fulfil an essential role in the hydrological cycle. Aerosols can originate directly from volcanoes, dust storms, sea spray, natural ecosystems, wildfires (including controlled burning), biofuel burning and fossil fuel burning, and a range of other sources, and indirectly via secondary reactions of plant compounds.

By volume, mineral dust and sea-salt are by far the most common aerosols, with significant amounts (in descending order) of sulfates, industrial dust, secondary organic, nitrates, primary biogenic, and soot (Posfai and Buseck 2010), though it is the biological emissions of our seas and vegetation that are primarily responsible for our rainfall.

Aerosols can directly affect the climate by scattering and/or absorbing solar and thermal radiation, or indirectly by acting as cloud condensation nuclei (CCN) and ice nuclei (IN). The chemical composition of the aerosols determine their climatic impact, some reflect solar energy (i.e. sulfates and organics), some strongly absorb solar energy (i.e. black carbon, iron oxide, some organic acids), and some (i.e. sulfate, nitrate and soluble organics) form cloud droplets. Research suggests that aerosol effects are of comparable importance to greenhouse gases as a driver of recent climate trends in the Southern Hemisphere, including Australia (Rotstayn *et. al.* 2008).

Ecological processes have evolved over millions of years and so are complex and multi-dimensional. Having evolved mechanisms to attract atmospheric moisture to them, trees then need to make it rain. Makarieva and Gorshkov (2010) describe the basic physical process: "*most moisture precipitates in the acceptor region where the moist air ascends and vapour condenses, with spatial fluctuations of this process dictated by local turbulent eddies*", though the condensation is largely due to the plants themselves.

Aerosols act as cloud condensation nuclei (CCN) for the formation of clouds, without them cloud droplets cannot form and rain cannot fall. CCN are key elements of the hydrological cycle and climate on regional as well as global scales

Vertical air motions (updrafts), or the mixing of air masses with different temperatures and moisture contents, can lead to the super saturations necessary for cloud formation.. Once CNN have activated the formation of cloud droplets, their continued growth occurs by the deposition of water vapour for as long as water supersaturation is maintained by persisting vertical motion. Water droplets grow by colliding and merging to create larger droplets. The types and quantities of aerosols affect water droplet size and abundance, reflection of solar radiation, and precipitation efficiency. The resultant clouds cover about 60% of the earth's surface and themselves cool the Earth's atmosphere system, as well as precipitating rainfall.

The presence of ice particles in clouds is also a major factor in the formation of precipitation, particularly at lower temperatures. Ice nucleation is the primary process of ice generation. As with water droplets, both inorganic and organic particles have been identified as nucleation agents. Freezing of water occurs at –36 to –38^{o}C. Soot, mineral dust, volcanic ash, and pollen have been found to be potentially important ice nuclei below about -15^{o}C, and fungal spores below about -30^{o}C (Murray *et. al.* 2012), though various bacteria occurring on plants have been found to act as ice nucleation agents at temperatures below -2^{o}C (Lindow *et. al.* 1978, Möhler *et. al.* 2007, Murray *et. al.* 2012. Hill *et. al.* 2014). While it has been postulated that bacteria may be a significant factor in atmospheric ice nucleation, and thus rainfall, Murray *et. al.* (2012) note that "*it is still under debate if there are sufficient bacteria in the atmosphere to have a significant impact*".

Once ice crystals form, the lower vapour pressure of ice favours a transfer of water mass from water droplets to the ice particles, enabling them to grow, they also collect droplets as they fall by collisions with water droplets that freeze on impact.

Aerosols that scatter sunlight reduce the energy flux at the surface of Earth and those that absorb solar radiation cause a warming of the atmosphere but a cooling of Earth’s surface. Overall, such aerosols are thought to have resulted in a cooling effect on the earth's surface and counteracted some of the warming due to increasing atmospheric CO^2 (Ramanathan and Carmichael 2008, Posfai and Buseck 2010).

The abundance of anthropogenic aerosol pollutants from cars, planes, factories and fires are generally considered to dramatically increase CCN concentrations, thereby reducing the size of cloud droplets so that they tend not to coalesce to form the large drops and fall as rain, thus increasing cloud albedo, reflection of sunlight, extending the life of clouds and reducing rainfall (Roberts *et. al.* 2003, Lohmann and Feichter 2005, Rotstayn *et. al.* 2008, Ramanathan and Carmichael 2008, Gunthe et. al. 2009, Posfai and Buseck 2010, Ackerley *et. al.* 2011, Tavares 2012, Pöhlker *et. al.* 2016), though this can vary with different cloud types, and whether pollutants enhance or suppress rainfall remains a contentious issue (Rotstayn *et. al.* 2008, Gunthe *et. al.* 2009). For a cloud with a given water content, an increase in the number of aerosol particles results in a proportional increase in droplet number and a decrease in droplet size, producing an increase in cloud albedo (Twomey 1977). Because small droplets are less likely to precipitate than large ones, the lifetime of clouds is extended (Albrecht 1989).

1.4.1. Biogenic Aerosols

Emissions from the ocean and from terrestrial vegetation are the main biogenic aerosol sources. Sea-salt particles arise through the bursting of bubbles that rise to the sea surface. The surface microlayer of the ocean is enriched in microorganisms, viruses, and extracellular biogenic material which can enter the atmosphere by bubble bursting, with sea-salt particles comprised of around 10% organic matter (Posfai and Buseck 2010).

Vegetation can release primary aerosol particles and generate secondary biological aerosol particles. Under natural conditions biogenic aerosol emissions provide most of the cloud condensation nuclei and are thus responsible for most rainfall. For example, in the Amazon, outside the burning season, Whitehead *et. al.* (2016) found that organic material contributed around 81% of the total mass of aerosols, with the balance of non-biological particles largely consisting of advected Saharan dust and sea salt from the Atlantic. Obviously closer to the coast marine aerosols become more significant.

Natural terrestrial primary aerosols can include significant organic matter, particularly of pollen, fungi and plant spores, leaf fragments, and bacteria (Möhler *et. al.* 2007, Tavares 2012, Whitehead *et. al.* 2016). Whitehead *et. al.* (2016) found that in the Amazon primary biological aerosols were dominated (around 70%) by fungal spores. Biogenic aerosols occur at relatively low densities and so are capable of attracting a great deal of water vapour and forming large, heavy droplets that rapidly precipitate. Emissions can total about half a ton per ha/year (Tavares 2012). A high proportion of natural aerosol particles act as CCNs, about 60 to 80 percent in the Amazon (Tavares 2012).

Volatile organic compounds (such as terpenes and isoprene) emitted from vegetation can oxidize in the atmosphere to form secondary organic aerosols that are CCN. It may be that these are "*the major and least studied aerosol source in Australia*" (Rotstayn *et. al.* 2008). Scott *et. al.* (2014) estimate that secondary organic aerosols increase the global annual mean concentration of cloud condensation nuclei by 3.6–21.1% and global annual mean cloud droplet number concentration by 1.9–5.2%, with increases being most significant over forested regions.

Volatile organic compounds (VOCs) are organic compounds that readily diffuse into the air. They include both human-made and naturally occurring chemical compounds. The majority of biologically generated VOCs are produced by plants, such as plant scents and the blue haze characteristic of eucalypt forests. Not only do they play an important role in communication between plants, and messages from plants to animals, but also between plants and moisture-laden air.

Trees, in particular, are efficient emitters of volatile organic compounds (VOC) that react with atmospheric oxidants to form aerosols that serve as CCN (cloud condensation nuclei). Studies in the pristine Amazon rainforest showed that fine particles (which account for most of the cloud condensation nuclei) consist mostly of secondary organic material derived from oxidized biogenic gases (Whitehead *et. al.* 2016).

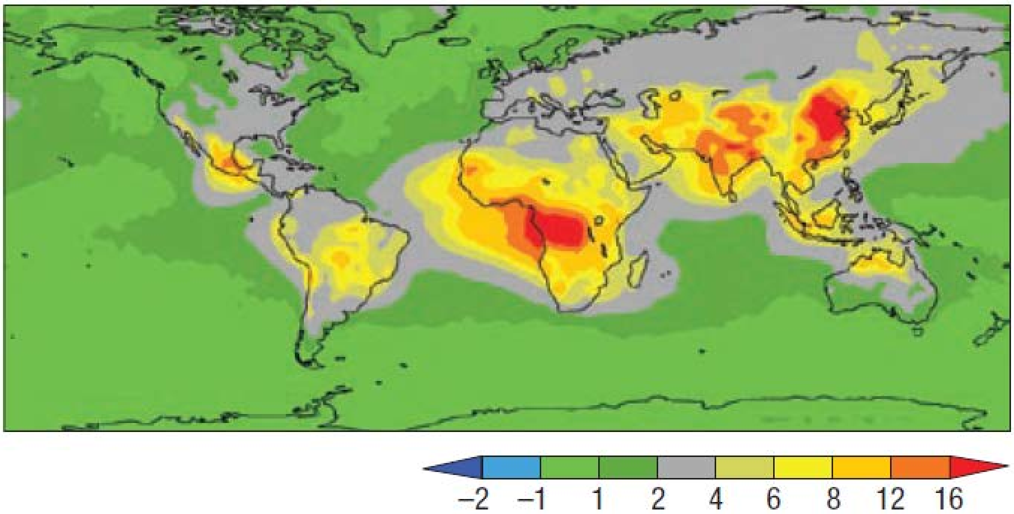
Eucalypt forests appear to be particularly efficient at producing VOC that develop into secondary aerosols. Suni *et. al.* (2008) found that the eucalypt forest they studied was a very strong source of new aerosol particles with formation events taking place on 52% of the days, which is 1.9 to 3.4 times as often as found in Nordic field stations. They also found that in summer and autumn nocturnal production was the major mechanism for aerosol formation.

1.4.2. Soot Aerosols

Soot is the strongest absorber of solar radiation among all major aerosols (Posfai and Buseck 2010). Globally, the annual emissions of soot (black carbon) are (for the year 1996) ~8 Tg yr^{-1}, with about 20% from biofuels, 40% from fossil fuels and 40% from open biomass burning (Ramanathan and Carmichael 2008). Biomass burning produces atmospheric particles in amounts that affect both the regional and global climate (Posfai and Buseck 2010, Ackerley *et. al.* 2011).

Soot mixes with sulphates, nitrates, organics, dust and sea salt to form 'atmospheric brown clouds'. Their concentrations peak close to major source regions and give rise to regional hotspots of soot-induced atmospheric solar heating.

From their study of atmospheric brown clouds over the Indian Ocean and Asia, Ramanathan *et. al.* (2007) found that atmospheric brown clouds resulted in a tenfold increase in airborne soot and other aerosol particles that enhanced lower atmospheric solar heating by about 50 per cent, with 90% of this increase attributable to soot, concluding "*that atmospheric brown clouds contribute as much as the recent increase in anthropogenic greenhouse gases to regional lower atmospheric warming trends*".



Atmospheric solar heating due to soot from the study by Chung *et al*. for the 2001 to 2003 period. From Ramanathan and Carmichael (2008).

Ramanathan and Carmichael (2008) identify that in those regional hotspots experiencing 50% atmospheric solar heating there was a corresponding surface cooling (dimming) of 5 to 10%. In relation to the redistribution of solar warming from the surface to the atmosphere, Ramanathan and Carmichael (2008) comment "*globally, this redistribution can weaken the radiative–convective coupling of the atmosphere and decrease global mean evaporation and rainfall*"

Ramanathan and Carmichael (2008) consider that soot's climate change forcing is as important as greenhouse gasses in the observed retreat of over two thirds of the Himalayan glaciers. They also identify that the deposition of soot over snow and sea ice may have resulted in an Arctic surface warming trend of as much as 0.5 to 1°C due to surface darkening, and that soot has caused changes in South Asia's monsoons because of reduced evaporation (surface cooling) and weakened monsoonal circulation (reduced sea surface temperature differentials).

The increased aerosols generated by smoke and anthropogenic sulfate aerosols can depress rainfall by reducing the size of cloud droplets, allowing the clouds to travel further from their origin (Lohmann and Feichter 2005, Ramanathan and Carmichael 2008, Ackerley *et. al.* 2011, Tavares 2012). Smoke also increases the number of “black carbon” aerosols that absorb solar energy, increasing atmospheric heat which can cause cloud droplets to evaporate before precipitating, thus intensifying the rainfall suppression (Ramanathan and Carmichael 2008, Tavares 2012). Roberts *et. al.* (2003) considered their "*modeling studies suggests that absorption of sunlight due to smoke aerosol may compensate for about half of the maximum aerosol effect*".

Ackerley *et. al.* (2011) also identify that sulfate aerosol particles can act directly on climate by scattering or absorbing radiation, and by changing the albedo of clouds making them more or less reflective. From their modelling Ackerley et. al. (2011) concluded that increases in aerosol loading cause a reduction in rainfall, finding for the drought stricken Sahel in central Africa "*that historical SO^2 emissions are likely to explain most of the 1940–80 rainfall changes and a significant proportion of the more pronounced 1950–80 drying*".

Soot is removed from the atmosphere by rain and snowfall and is considered to have an atmospheric lifetime of about one week, though its atmospheric longevity can be extended where it suppresses rainfall.

Biomass burning is one of the main sources for carbonaceous aerosol in the atmosphere, globally contributing about 40% of CO^2, 32% of CO, 38% of tropospheric ozone, 7% of total particulate matter and 39% of particulate organic carbon (Dentener *et. al.* 2006). Bushfires inject large volumes of particulate matter into the Australian atmosphere every year, contributing around 5% of the worlds annual emissions (Rotstayn *et. al.* 2008).

In the Amazonian rainforest widespread biomass burning in the dry season can result in a substantially increased aerosol optical depth over large areas of Amazonia, as well as modified cloud properties and suppressed precipitation (Roberts *et. al.* 2003, Whitehead *et. al.* 2016)

Nothing in nature is ever simple. Graf *et. al.* (2007) investigated the effects of aerosols from the 1997 Indonesian fires, finding *" although the monthly mean rainfall is depressed over most of the heavily polluted areas, there are coherent areas, which are also polluted, where the opposite is the case. ... mainly over or in proximity to the sea, where moisture supply is high".*

Rotstayn *et. al.* (2008) consider that Asian anthropogenic aerosols, largely generated by forest and peat fires, can affect monsoonal rainfalls in Australia. They hypothesise that aerosols cool the Asian continent and surrounding oceans, increasing the temperature gradient and monsoonal winds between Asia and Australia, which bring increased rainfall to northern Australia. Without this effect north-west Australia could expect declining summer rainfall in response to climate change.

Rotstayn *et. al.* (2008) consider "*that aerosol effects are of comparable importance to greenhouse gases as a driver of recent climate trends in the Southern Hemisphere, including Australia*".

Ramanathan and Carmichael (2008) consider in relation to Black Carbon (soot):

> *Given that BC has a significant contribution to global radiative forcing, and a much shorter lifetime compared with CO2 (which has a lifetime of 100 years or more), a major focus on decreasing BC emissions offers an opportunity to mitigate the effects of global warming trends in the short term .... Reductions in BC are also warranted from considerations of regional climate change and human health*
>
> *... the elimination of present day [atmospheric brown clouds] ABCs through emission reduction strategies would intensify surface warming by about 0.4 to 2.4 ºC... If on the other hand, the immediate target for control shifts entirely to BC (owing to its health impacts) without a reduction in non-BC aerosols, the elimination of the positive forcing by BC will decrease both the global warming and the retreat of sea ice and glaciers. It is important to emphasize that BC reduction can only help delay and not prevent unprecedented climate changes due to CO^2 emissions.*

1.4.3. Dust Aerosols

Desert dust can be the dominant particle type even thousands of kilometers from the source. In addition to its direct and indirect climate effects, atmospheric dust plays an important role in the global biogeochemical cycle of iron, a limiting nutrient in many oceanic ecosystems (Posfai and Buseck 2010). Australia contributes more than 70% of the atmospheric dust loading over most of the Southern Hemisphere (Rotstayn *et. al.* 2008). Posfai and Buseck (2010) suggest *"that mineral dust is a potential cleansing agent for organic pollutants".* Dust generation is episodic, mostly related to droughts. When dust is blown out to sea to the north-east or north-west it can potentially affect cyclone activity in the Australian region, and when blown to the southern ocean the iron-rich dusts stimulate phytoplankton growth (Rotstayn *et. al.* 2008).

1.5. Soil Moisture

Recycling of rainfall back into the atmosphere as water vapour by evapotranspiration is one of the most important land–atmosphere interactions in the climate system. While evaporation from water, land and vegetation surfaces makes a significant contribution to water recycling, it is transpiration of soil moisture by vegetation that is most significant. Thus the availability and accessibility of soil moisture are key drivers of the hydrological system. Any increase in runoff implies a decrease in water available for recycling by evapotranspiration.

When rain falls some is intercepted by ground and vegetation surfaces where it can be rapidly evaporated back into the atmosphere, and some is rapidly transported by overland flow directly into streams, though most is captured as soil moisture or groundwater where its movement is slowed. Once in the soil it is available to plants for transpiration, until it seeps into streams or deep aquifers out of reach.

Soil moisture and groundwater are essential for slowing down and evening out the water cycle, extending the accessibility of water for plants over weeks, months and years. A wet episode can influence groundwater contribution to summer evaporation for several years afterwards. For their study area, Lam *et. al.* (2011) consider the time scale to transport water tens of kilometers in the subsurface is a minimum of tens of years, and at maximum tens of thousands of years, compared to atmospheric processes that can take hours.

Soil moisture can directly affect rainfall through evapotranspiration (Guo *et. al*. 2006, Lam *et. al.* 2007). Lam *et. al.* (2007) found "*In a surprisingly large part of the land surface, soil moisture influence on precipitation occurrence is of the same order of magnitude as the influence of the annual cycle*". Guo *et. al.* (2006) examined the impacts of soil moisture conditions on rainfall generation for the boreal summer season using a range of models, concluding that soil moisture has a significantly strong impact on rainfall in the "*transition zones between dry and wet areas, where evapotranspiration variations are suitably high but are still sensitive to soil moisture*". In dry areas evapotranspiration rates "*are sensitive to soil moisture, but the typical variations are generally too small to affect rainfall generation*".

Deforestation can have a significant effect on the water-cycle by increasing surface run-off (thereby reducing the water available to replenish soil reserves), by changing deep rooted vegetation to shallow-rooted vegetation (thereby reducing the accessible volume of soil moisture), and altering watertables. This means that less water is available for recycling by transpiration, particularly in dry periods.

Sheil and Murdiyarso (2009) state:

> *Water reserves are important. Plants with high stem volumes allow transpiration to outstrip root uptake, as stem water reserves are depleted by day and replenished at night (Goldstein et al. 1998, Sheil 2003). Trees (and forest lianas) typically have deeper roots than other vegetation and can thus access subterranean moisture during droughts (Calder et al. 1986, Nepstad et al. 1994). Many forest soils possess good water infiltration and storage—properties often lost with deforestation (Bruijnzeel 2004). Vertical translocation of soil water through the forest soil profile by roots at night may also be important (Lee et al. 2005).*

Rahgozar *et. al.* (2012) undertook a comparison of the water budgets of grasslands and forests in Florida, finding that annual totals of evapotranspiration averaged 850mm for grassland and 1100mm for the alluvial wetland forest, and that grasslands intercepted less rainfall, had higher runoff, lower infiltration, and higher watertables.

Von Randow *et. al.* (2004) undertook comparisons of soil moisture down to 3.6m in Amazonian pasture and rainforest, finding similar use of soil moisture in the top 2m of the soil profile, with rainforest using more moisture towards the end of the dry season and less in the wet season. Below 2m depth the pasture had little effect on soil moisture, whereas the rainforest made substantial use of deep soil moisture during the dry season. von Randow *et. al.* (2004) comments:

> *The pasture vegetation withdraws water only from the upper layers of the soil with the water stored in the layer from 2 to 3.4m deep showing only little variation, mainly caused by drainage. In the forest, on the other hand, the soil water storage changes more rapidly in this layer – the seasonal change was about 290mm in the forest and 110mm in the pasture.*

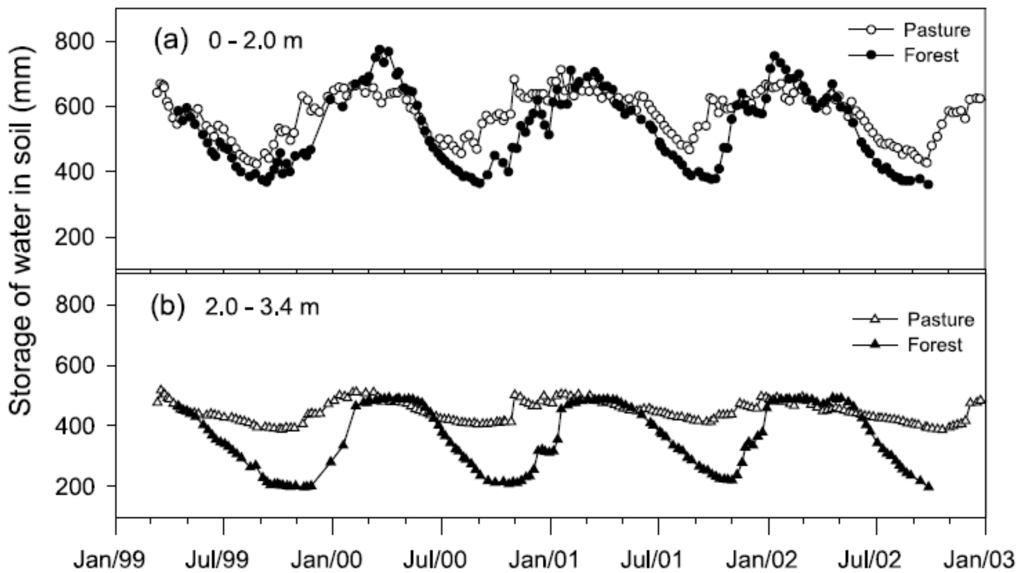


Fig. 5 from von Randow *et. al.* (2004): Storage of water in the soil at forest and pasture sites, for the layers from (a) 0–2m and (b) 2–3.4m deep

In their Western Australian study, Nair *et. al.* (2011) found that transpiration from the native vegetation is less sensitive to soil moisture availability than nearby croplands, observing:

> *The deep rooted native vegetation has access to the underground aquifer whereas the shallow rooted agricultural crops are reliant on near-surface soil moisture and hence their greater sensitivity to soil moisture. One of the consequences of replacing native vegetation with agricultural crops is the removal of this link between the underground aquifer and the atmosphere.*

1.5.1. Runoff

Australia's low and highly variable rainfall pattern, and the use of most rainfall by vegetation, means that we have one of the lowest amounts of runoff to rivers and deep drainage to groundwater in the world. Native vegetation in semi-arid Australia is dominated by trees or woody shrubs with relatively deep roots that is effective at taking full advantage of any available water, using most of the rainfall in ways that minimize the amount of water that leaks past the root zone. (Williams *et. al*. 2002)

The evidence is that by reducing rainfall interception by vegetation, reducing evapotranspiration and changing soil properties, deforestation generally results in an increase in runoff to streams (Bosch and Hewlett 1982, Williams *et. al*. 2002, Silberstein *et. al.* 2003, Bari and Ruprecht 2003, Brown *et. al.* 2005, Bagley 2011). The increased runoff can result from changes in surface runoff or changes in baseflow. Surface runoff increases where the infiltration ability of the soil is reduced (such as by compaction), when the effectiveness of surface vegetation and leaf litter to slow overland flows is reduced (providing less time for infiltration), or when raised watertables reduce the storage capacity of the soil.

Silberstein *et. al.* (2003) and Findell *et. al.* (2007) identify that when the watertable comes too close to the surface that there is an increase in saturated areas, and a reduced maximum water holding capacity of the remaining unsaturated soils, and hence an increase in surface runoff, and potentially flooding, leaving less moisture available for evapotranspiration.

Williams *et. al*. (2002) consider that in Australia large scale clearing of native vegetation and its replacement with annual crops and pastures have substantially increased the amount of water leaking beneath the root zone and entering the internal drainage and groundwater systems of the landscape.

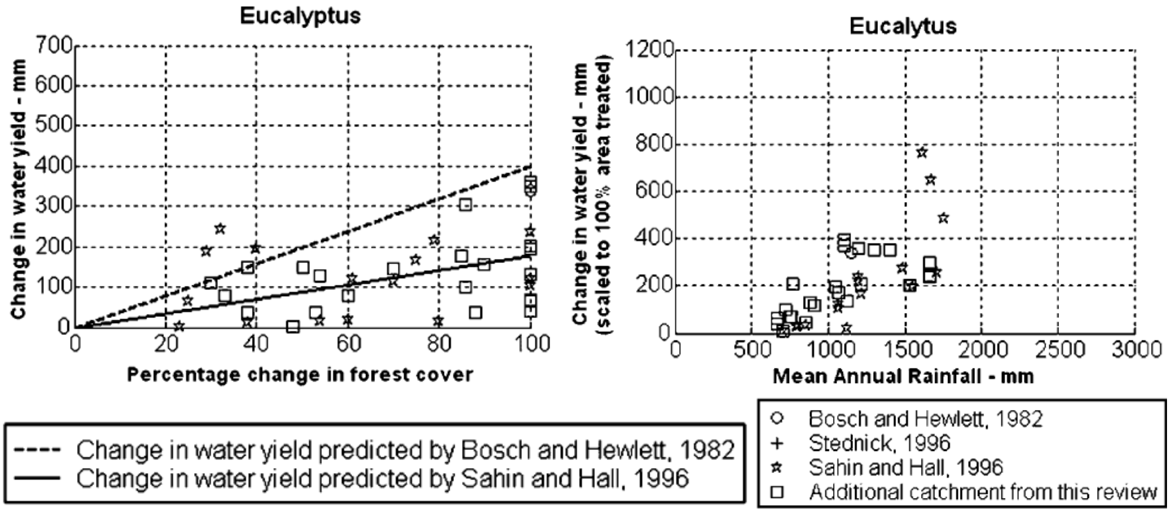
Ruprecht and Schofield (1991a, b) partially deforested (western 53% of the catchment) a small (344ha) experimental catchment in southwest Western Australia in 1976 to study the effects of agricultural development on water quantity and quality, finding:

> *The impact on the groundwater system in the cleared area was dramatic. Initial rates of rise were only 0.11 m year^{-1} but this increased after 10 years to average 2.3 m year^{-1}. Groundwater rises of 15 m in the valley and 20–25 m on the lower sideslopes were observed over 13 years. A small seep (groundwater discharge area) appeared for the first time in 1988 and by 1989 it covered an area of 1 ha. Streamflow initially increased by 30 mm year^{-1} (4.0% rainfall) compared with a native forest average streamflow of 8 mm year^{-1} (1.0% rainfall). However, since the seep area developed, the increase in streamflow has been 50 mm year^{-1} (6.6% rainfall).*

Ruprecht and Schofield (1991b) report on subcatchments in an area of 300ha subject to partial clearing noting:

> *Within subcatchments that were 60–70% cleared, groundwater level rises were observed of 7.8–10.2 m compared with a 5.8 m rise with 32% clearing and a 2.3 m fall in a native forest control, from 1977 to 1989. The combination of clearing treatments affecting 38% of the catchment has resulted in a modest (13 mm) increase in catchment streamflow. This was over double the average forested streamflow.*

From their review, Bosch and Hewlett (1982) concluded that for each 10% reduction in eucalypt cover there is an increase of around 40mm in annual water yield. From their review of paired catchments, Brown *et. al.* (2005) found that all studies identified similar trends for eucalypt forests, pine forests, hardwood and scrub, with variable magnitudes of runoff increases. Runoff increased in line with the percentage cleared, though for any impact of vegetation change to be detected at least 20% of the catchment needed to be treated. Changes in runoff also increased in line with rainfall.



Extracts of Figs. 1 and 2 from Brown et. al. (2005): Water yield changes as a result of (LEFT) changes in vegetation cover and (RIGHT) as a function of mean annual rainfall (from Bosch and Hewlett (1982), Sahin and Hall (1996) and Stednick (1996)).

Bagley (2011) consider that in the tropics deforestation increases surface runoff, which alters river flow, noting "*Since 1970 the Araguaia River in east-central Brazil has experience a 25% increase in discharge, with recent modeling efforts suggesting that deforestation in the region was responsible for nearly 2/3 of the increase*".

Studies in experimental catchments in the south–west of Western Australia examined the impacts of clearing for agricultural development on water yields to streams (Bari and Ruprecht 2003), finding that clearing led to permanent increases of water yield of about 30% of annual rainfall for high rainfall areas (1100 mm mean annual rainfall) and 20% of annual rainfall for low rainfall areas (900 mm annual rainfall).

All else being equal, water that is lost from a catchment as runoff is no longer available for recycling by evapotranspiration, so deforestation or modification of vegetation that results in an increase in runoff is effectively reducing atmospheric moisture by a corresponding amount.

While the evidence is that permanent clearing of native vegetation results in an increase in runoff to streams, which can largely be attributed to a reduction in evapotranspiration, it is equally clear that activities such as logging and thinning can result in reduced runoff over time. The generalised pattern following heavy and extensive logging of an oldgrowth forest is for there to be an initial increase in runoff peaking after 1 or 2 years and persisting for a few years. Water yields then begin to decline below that of the oldgrowth as the regrowth uses more water. Water yields are likely to reach a minimum after 2 or 3 decades before slowly increasing towards pre-logging levels in line with forest maturity. (Kuzcera 1987, Vertessy *et. al.* 1998, Cornish and Vertessy 2001, Bari and Ruprecht 2003, Brown *et. al.* 2005, Burrows *et. al.* 2011).

This is explored in more detail in Section 2.4 of this review.

1.5.2. Rooting Depth

Roots provide the basis for plant growth, providing access to both water and nutrients. Along with litter fall, roots are the primary input of organic carbon into the soil, with below ground carbon storage more than twice aboveground storage (Jackson *et. al.* 1996) . Below ground primary production is often 60-80% of total net primary production (Jackson *et. al.* 1996).

Evaporation is only effective for water at or near the earth's surface, whereas plant roots are able to tap into soil moisture and groundwater deep below the surface and recycle the water into the atmosphere by transpiration. The process of evaporation can access surface soil moisture, varying with soil type and structure, through diffusion (the movement of water along a concentration gradient from wet soils to dry). The evaporative "extinction depth" is the depth below which no further movement of water towards the surface occurs via diffusion. For bare sandy soils the extinction depth has variously been identified as 50-100cm (Mughal *et. al.* 2015).

The roots of plants allow access to water at greater depths depending on their rooting depth. The deeper the roots go, the larger volume of soil moisture that can be accessed. Soil mycorrhiza and diffusion allow access to moisture deeper than the root zone.

Zang *et. al.* (2001) note "*studies indicate that deep roots play an important* hydrological role *in plant systems, especially under dry conditions ... As the soil progressively dries, more water is extracted from deeper layers to keep stomata open. As a result, trees are able to maintain a relatively constant evapotranspiration rate over time, even when soil moisture in the upper part of the soil is limited. Under such conditions, shallow-rooted plants tend to close their stomata and have a reduced evapotranspiration rate. In regions with dry climates, plant-available water capacity is expected to be a main reason for differences in annual evapotranspiration between trees and shallow-rooted plants".*

Most roots are near the surface and diminish in volume with depth. Root depth can be limited by physical barriers or adverse soil conditions. Roots can find ways through barriers to extend to greater depths, and often extend down to water tables. Stone and Kalisz (1991) identify that roots near a water table may be more effective in absorption by 1000 times or more than those in drier soil above.

Jackson *et. al.* (1996) found that tundra, boreal forest, and temperate grasslands have the shallowest rooting profiles, with 83-93% of roots occurring in the top 30cm of soil, compared to deserts and temperate coniferous forests showed the deepest rooting profiles, with only 50% of roots in the uppermost 30 cm. Root biomass also varied greatly from forests and sclerophyllus shrublands with a maximum of 5kg m^{-3} (rainforests with densities of over 40 kg m^{-3} in the shallowest depths) down to croplands, deserts, tundra and grasslands, all of which had a root biomass <1.5 kg m^{-3}. (with never more than 5kg m^{-3} in the most densely rooted cases).

Eamus *et. al.* (2002) found savanna eucalypts had a root biomass up to 12.83 kg m^{-3}. Eamus *et. al.* (2002) excavated down to 2m, finding 77-90% of total root biomass in the upper 0.5 m of soil, with about 5 % in the next 0.5 m and 5-15 % in the 1- 2 m depth range, noting:

> *The rapid decline of biomass with depth was because of the steep decline in coarse root biomass rather than fine roots which were more evenly distributed with depth. Such a distribution of fine roots is required if, as calculated by Cook et al. (1998), water must be extracted from the entire upper 6-8 m of soil to account for the observed rate of canopy water use in the dry season. Therefore fine root biomass should be significant at depth.*

In their literature review relating to root depth, Stone and Kalisz (1991) identify a range of recorded maximum root depths for various eucalypt species from 1.5-60m. Of the 22 recorded depths, 9 were 15m or more, with the maximum depths given as 40m, 45m,and 60m. They also report root depths of 10m for 15m high Eucalyptus signata forest and 18m for <8m high Mallee.

Jackson *et. al.* (1996) identify that roots of one species have been recorded extending down 50m. Lima (1984) notes claims of eucalypt root penetration of up to 18m and well over 30 m, and that some eucalypt species are characterized by developing shallow root systems, whereas some species have inherently deep-going main roots.

One of the key problems in identifying the importance of deep roots is that most root studies are limited to <1m depth, and very few extend to >2m depth, so there is a paucity of information on the depths to which roots go (Lima 1984, Stone and Kalisz 1991).

Many researchers have identified the reduction in vegetation rooting depth caused by deforestation as having a key role in reducing rainfall (i.e. Nobre *et. al* 1991, Hoffmann and Jackson 2000, Foley *et. al.* 2003, Findell *et. al.* 2007, Findell *et. al.* 2009, Lawrence and Chace 2010, Bagley 2011, Jasechko *et. al*. 2013). Bagley (2011) found that deforestation dried the soil during drier periods, concluding "*the replacement of tropical forest with shrubby grasses removed the ability of vegetation to access moisture in deeper soil levels, forcing the vegetation to pull more moisture from top soil layers and less from lower layers*".

The reduction in vegetation rooting depth is also considered to have a significant effect of energy flows because the reduced transpiration means less conversion of energy to latent heat and thus increased ground temperatures (*von Randow, et al.*, 2004, Findell *et. al.* 2007, Findell *et. al.* 2009, Bagley 2011), as noted by Bagley (2011):

> *in the case of tropical deforestation shallow grasses and shrubs commonly replace large leafy trees with long roots capable of reaching water deep in the soil (Culf et al., 1996; Davin and de Noblet-Ducoudré, 2010). The grasses are incapable of releasing the same amount of energy and moisture in the form of latent heat flux as the trees. As a result, evaporative cooling decreases, the local temperature increases, and sensible and radiative fluxes rise.*

2. THE DRYING OF AUSTRALIA

It is apparent that the arrival of Aboriginal people some 50,000 years ago led to changes to the vegetation of Australia by their use of fire as a land management tool. It has been suggested that these changes caused a reduction in woody vegetation and an increase in grasslands of sufficient magnitude to cause a drying of large areas of the continent, and increasing aridity, such as in central and north-west Australia.

The more recent arrival of Europeans initiated widespread clearing in the better watered areas, as well as extensive vegetation modification through logging and grazing. Around 15% of the Australian continent has been cleared of native vegetation, including 22% of forests and woodlands, and some 48% of the continent comprises native vegetation used for grazing and logging. These massive changes have had major ramifications for the climates in the regions most affected.

Rainfall is declining in southern and eastern Australia, as temperatures are rising. . Rainfall has been declining seasonally in the most heavily cleared areas, with abrupt reductions in the 1970s in south-western Australia and eastern Queensland. Autumn rainfall over Victoria declined by about 40% over 1950–2006. From the mid-1990s to late 2000s, many Australian regions were plagued by concurrent severe droughts, which later became known as the Millennium Drought, the most severe in recorded history.

Deforestation has significantly contributed to these climatic trends by reducing transpiration by vegetation, reducing the ability of vegetation to attract moist air, reducing the ability of tall rough vegetation to slow winds and increase rainfalls, reducing the availability of aerosols to act as cloud condensation nuclei, reducing evaporative cooling and cloud cover, and increasing runoff.

The removal of deep rooted forests and woodlands has reduced evapotranspiration and allowed saline ground-waters to rise over large areas of Australia, with 5.7 million hectares currently at risk of dryland salinity. This could rise to over 17 million hectares by 2050. This has turned many of our rivers saline, caused widespread degradation of native ecosystems and agricultural lands, destroyed infrastructure, and diminished biodiversity.

Logging confounds these changes because after some years regrowth trees can increase transpiration and the transfer of soil moisture to the atmosphere. The widespread conversion of oldgrowth forests to regrowth has reduced runoff to streams, and the increased demands of the regrowth seems to be exceeding available soil moisture in some areas, causing significant water stresses in drier catchments and increasing deaths of trees in droughts. The overall impacts on rainfall caused by the conversion of oldgrowth forests to regrowth remain unknown.

It is apparent that climate change due to increasing CO^2 is compounding the impacts of deforestation, and will become the dominate influence into the future, though it may not be primarily responsible for the climatic changes Australia has experienced so far.

2.1. The Early Changes

Significant anthropogenic changes to the Australian climate are likely to have originated with the Aborigines some 50,000 years ago because of their use of fire to manage vegetation.

Considerable attention has focussed on the effects of vegetation changes on the Australian monsoon. Studies have identified a reduction in woody vegetation and increase in grasses is likely to have occurred in central Australia around 50,000 to 40,000 years ago (the late Quaternary) due to Aboriginal burning practices, such vegetation changes are likely to have had significant effects on northern Australia's climate, weakening the continental penetration of the summer monsoon., thereby creating vegetation feedbacks (Johnson et. al. 1999, Bowman 2002, Miller *et. al* 2005, Miller *et. al.* 2007, Notaro *et. al.* 2011, Wyrwoll *et. al.* 2013).

Traditional burning practices across northern Australia were undertaken systematically throughout the dry season, in part to promote grasses as feed for kangaroos for hunting. Miller et. al. (2007) note:

> *Fire can be an effective agent of ecosystem change. Humans have had controlled use of fire since the Middle Quaternary. They burn landscapes for many purposes, from clearing passageways and hunting along the fire-front, to signalling distant bands and promoting growth of preferred plants.*

This burning regime has resulted in significant vegetation changes, for example Bowman *et. al.* (2010) observe:

> *Prior to the arrival of people in the Australian–New Guinea region, the fire regime was most probably characterized by infrequent high-intensity fires (Bowman, 2002). Thus prehuman landscapes are likely to have been different from today, with fire-adapted species less abundant, the savanna (mixtures of tropical grass and trees) more geographically restricted, and evergreen dry forests and rain forests more widespread.*

Such a landscape would have been cooler and wetter than today's savanna and desert landscape. Johnson *et. al.* (1999) assessed carbon isotopes in emu eggshells to identify broad vegetation changes in the Lake Eyre basin, leading them to conclude that identified vegetation changes around 40,000-50,0000 years ago were likely to be related to climate changes brought about by Aboriginal burning, concluding:

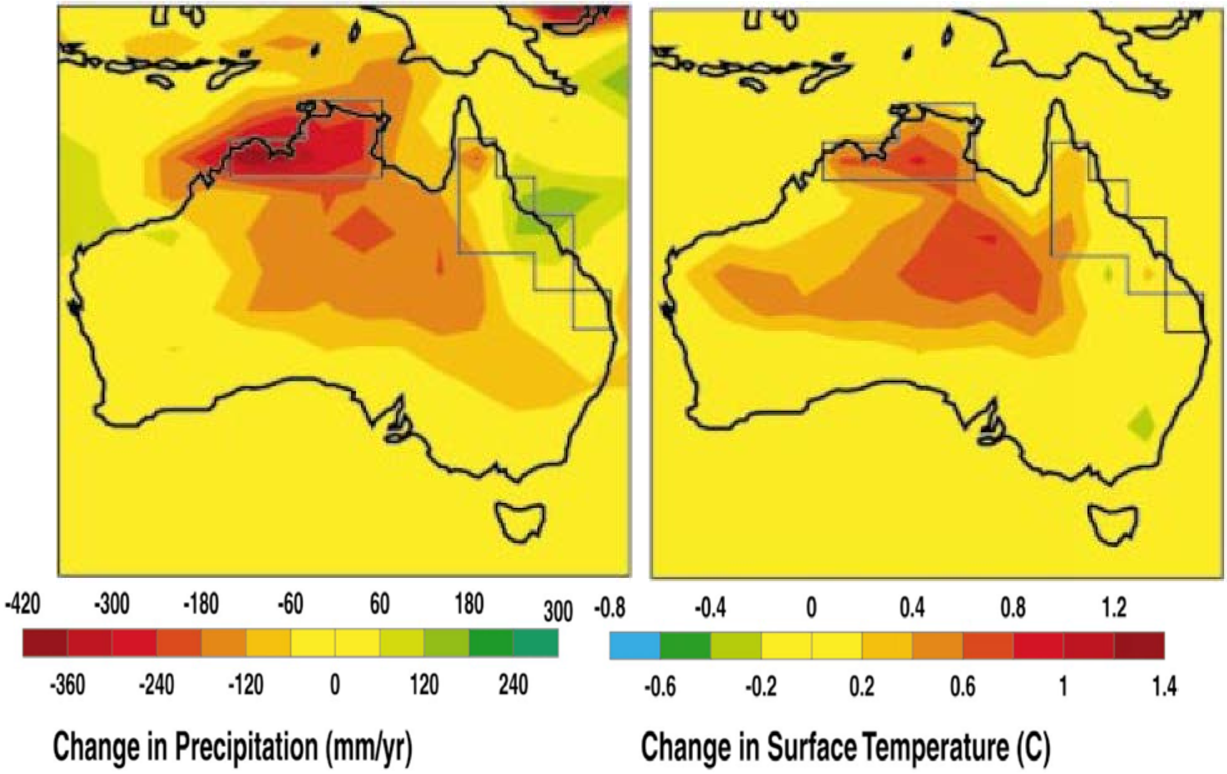
> *The effectiveness of the summer monsoon at Lake Eyre decreased substantially at approximately the same time as megafauna extinction (6) and never fully recovered, A change in vegetation type across northern Australia brought about by the burning practices of the first human colonizers may have reduced this wet season feedback and, consequently, diminished the effectiveness of the summer monsoon at Lake Eyre during the early Holocene*

Hoffmann and Jackson (2000) consider that "*Humans have increased the frequency of fire, primarily in moist tropical savannas where burning now typically occurs at intervals of 1–3 yr ... a rate that can greatly reduce savanna tree densities*". To assess the impact of conversion of savannas to grasslands they modelled changing woody plant cover from 50% to 0% in 5 moist savannas, including northern Australia. Hoffmann and Jackson (2000) found that tree reduction resulted in a significant increase in temperature and decline in precipitation in all savanna regions (except northern Africa). For northern Australian moist savannas they identified declines of 121 mm yr^{-1}

(13%) in precipitation, 70 mm yr^{-1} (9%) in evapotranspiration, 51 mm yr^{-1} (37%) in convergence, and 0.36°C in temperature. Their modelling shows impacts being most severe in the northern territory with impacts extending to encompass central Australia.

Hoffmann and Jackson (2000) conclude:

> *This study indicates that these dry periods may become more frequent following the conversion of savanna to grassland, a change that would have a negative impact on tree regeneration.*
>
> *These proposed negative effects on tree density would exacerbate the direct effects of humans on savanna vegetation. A reduction in precipitation brought about by anthropogenic vegetation change should drive further reductions in tree cover, as well as slow the succession of grassland to savanna. Thus any direct effect of humans on the savanna environment would be accelerated because of climatic feedbacks.*



Change in mean annual precipitation [LEFT] and surface air temperature [RIGHT] resulting from conversion of tropical savanna to grassland. Note the extent of impacts far from changed areas (grey squared outlines). From Hoffmann and Jackson (2000).

Johnson *et. al.* (1999)'s identification of likely climate changes resulting from Aboriginal burning generated considerable interest. A review Bowman (2002) concluded "*this interpretation is difficult to sustain given the great difficulty in extracting a clear 'signal' of an anthropic impact from the inherent variability and fragmentary record of the palaeo–summer monsoon".* Since then a variety of modelling studies have found that the likely magnitude of vegetation changes can significantly affect the pre-Monsoon climate (Miller *et. al.* 2005, Notaro *et. al.* 2011, Wyrwoll *et. al.* 2013)

From their modelling Miller *et. al.* (2005) concluded:

> *Additional simulations show that the penetration of monsoon moisture into the interior is sensitive to biosphere-atmosphere feedbacks linked to vegetation type and soil properties.*

> *This sensitivity offers a resolution to the observed failure of the Australian Monsoon to penetrate the interior in the Holocene. Postulated regular burning practiced by early humans may have converted a tree-shrub-grassland mosaic across the semiarid zone to the modern desert scrub, thereby weakening biospheric feedbacks and resulting in long-term desertification of the continent*

Miller *et. al.* (2007) analysed the eggshells of a large sample of emu shells, shells of the extinct *Genyornis newtoni* and wombat teeth, identifying a nearly continuous record of dietary intake for *emus* throughout the past 140 thousand years and for *Genyornis* before they became extinct around 45-50 thousand years ago. They consider "*Our eggshell and wombat tooth derived* [C3 and C4] *data provide firm evidence for an abrupt ecological shift around the time of human colonization and megafaunal extinction in Australia, between 50 and 45 ka*", which "*suggest a tree/shrub savannah with occasionally rich grasslands was converted abruptly to the modern desert scrub*", stating:

> *We speculate that ecosystem collapse across arid and semi-arid zones was a consequence of systematic burning by early humans. We also suggest that altered climate feedbacks linked to changes in vegetation may have weakened the penetration of monsoon moisture into the continental interior, explaining the failure of the Holocene monsoon. Climate modeling suggests a vegetation shift may reduce monsoon rain in the interior by as much as 50%.*
>
> *...*
>
> *The reduction in surface roughness, changed albedo, reduced recycling of rainfall by evapotranspiration, and more rapid runoff, all of which would accompany a transition from a treed-savannah to the modern desert scrubland, may have resulted in a significant weakening of monsoon rain over the Lake Eyre Basin, and even as far south as Port Augusta and the Darling-Murray Lakes throughout the Holocene*

Marshall and Lynch (2008) dismissed the results of Miller *et. al* (2005) on the basis of the "*extreme and idealistic scenarios tested in their study*", concluding from their modelling that:

> *The results of this study suggest that sea level and solar insolation variations over the Australian monsoon region are primarily responsible for the changes in the intensity, southward extent, and timing of the Australian summer monsoon over the last 55,000 years. Vegetation and greenhouse gas radiative forcing perturbations, on the other hand, are responsible for only small proportions of the variation in the simulated monsoon.*

Notaro *et. al.* (2011) criticise Marshall and Lynch (2008) for having *"applied a coarse global climate model coupled to a crude land surface model",* From their modelling Notaro *et. al.* (2011) found a significant climatic response to a 20% reduction in vegetation in the pre-Monsoon season, with decreases in precipitation, higher surface and ground temperatures, and enhanced atmospheric stability, leading them to conclude:

> *We find that a decrease in vegetation cover can delay the Australian monsoon and reduce early monsoon rainfall, and in this respect, our findings lend some support to the claim that Aboriginal vegetation burning practices over late Quaternary time scales impacted the northern Australian summer monsoon regime [Johnson et al. , 1999]. However, our results clearly demonstrate that the effect on the peak monsoon was limited [Pitman and Hesse, 2007; Marshall and Lynch, 2008]. But we have equally demonstrated that biophysical feedbacks associated with reduced vegetation cover can have a clear impact on the early/pre-monsoon season, leading to a significant reduction in precipitation and essentially extending the dry season.*

Wyrwoll *et. al.* (2013) reviewed previous studies and modelled the climatic impacts of reducing the total vegetation cover over northern Australia by 20% to simulate the effects of burning, concluding:

> *The results of this study indicated a significant climate response to reduced vegetation cover during the pre-monsoon period of November and December (Fig. 1a). Noteworthy is the delayed onset of the monsoon. Other prominent changes were decreases in total rainfall of more than 30 mm, higher surface and ground temperatures and enhanced atmospheric stability. ... no significant response is observed in monsoon precipitation following vegetation change, but feedbacks are evident in the pre-monsoon period.*
>
> *... we can conclude that through burning practices resulting in biome changes in northern Australia, indigenous people altered not only the ecology but also the climate of the region, effectively extending the dry season and delaying the onset of the "full" monsoon.*

For the East Asian monsoon, Fu (2003) assessed the effect of changes resulting from clearing of the potential natural landscape wrought by humans over the millennia. The impact from agrarian societies in that region have been far greater than Australia's 'firestick' hunter gatherers, with more than 80% of the region affected by conversion of various categories of natural vegetation into farmland, grassland into semi-desert and widespread land degradation. Though his study provides further evidence of the significant effect that vegetation changes can have on monsoons. Fu (2003) concluded:

> *... by altering the complex exchanges of water and energy from surface to atmosphere, the changes in land cover have brought about significant changes to the East Asian monsoon. These include weakening of the summer monsoon and enhancement of winter monsoon over the region and a commensurate increase in anomalous northerly flow. These changes result in the reduction of all components of surface water balance such as precipitation, runoff, and soil water content. The consequent diminution of northward and inland moisture transfer may be a significant factor in explaining the decreasing of atmospheric and soil humidity and thus the trend in aridification observed in many parts of the region, particularly over Northern China during last 3000 years*

In their study of East Asia's monsoon Lee *et. al.* (2011) similarly found that the "*monsoon can be weakened as potential (natural) vegetation is converted to bare ground or irrigated cropland*".

2.2. Changes since European Settlement

There have been major changes to Australia's vegetation since European settlement. Over the past 200 years some 15% of native vegetation had been cleared, and a significant proportion of the remaining vegetation has been degraded by grazing (McKeon *et. al.* 2004) and logging. Land clearing focussed on southeast Australia from 1800 to the mid-1900s, southwest Western Australia from the 1920s until the 1980s, and more recently inland Queensland. Rainfall has been declining in cleared areas, with abrupt reductions in the 1970s in south-western Australia and 1990s in south-eastern Australia. Climate change is now compounding the impacts of deforestation.

Clearing has focussed on forests and woodlands, with an estimated 20% of forests and 24% of woodlands cleared. As noted by Deo (2011) "*Within the intensive land-use zones of southeast and southwest Western Australia, approximately 50% of native forest and 65% of native woodland has been cleared or severely modified*".

Vegetation Type	*Pre-European (km2)*	*Current (km2)*	*Difference (km2)*	*Percentage lost (%)*
Forest	1,391,409	1,118,107	273,302	19.6
Woodland	2,710,459	2,066,153	644,306	23.8
Shrubland	1,470,614	1,411,539	59,075	4.0
Heath and Grassland	1,996,688	1,958,671	38,017	1.9
Total Native Vegetation	7,578,427	6,562,541	1,015,886	13.4

Aggregated changes in Australian vegetation cover, from The Native Vegetation Inventory Assessment (NVIS) of native vegetation by type prior to European settlement and as at 2001–2004 (Beeton *et al.,* 2006).

According to ABARE (2006) around 15% of the Australian continent has been cleared; 1,000,000 km^2 has been cleared for agriculture, 26,000 km^2 has been cleared for urban and residential, 1,700km^2 cleared for mining and waste, and 125,618 km^2 comprises natural and artificial water storages. Around 48% of the Australian continent comprises native vegetation used for grazing and logging; 3,600,000 km^2 of natural vegetation was used for grazing and 24,000 km^2 for logging. The remaining 37% is either protected in some form or has minimal use.

Bradshaw (2012) summarises:

> *Overall, Australia has lost nearly 40% of its forests, but much of the remaining native vegetation is highly fragmented. As European colonists expanded in the late 18th and the early 19th centuries, deforestation occurred mainly on the most fertile soils nearest to the coast. In the 1950s, south-western Western Australia was largely cleared for wheat production, ... Since the 1970s, the greatest rates of forest clearance have been in south-eastern Queensland and northern New South Wales, although Victoria is the most cleared state. Today, degradation is occurring in the largely forested tropical north due to rapidly expanding invasive weed species and altered fire regimes.*

Annual rates of clearing peaked during the 1970s when extensive areas were cleared in southwest Western Australia and Queensland for grain production and grazing pasture improvement, respectively (Deo 2011). Between 2000 and 2004 the rate of native vegetation clearance in Queensland was over 500,000 ha yr^{-1} primarily for grazing, ranking the region fifth worldwide on deforestation rate (McAlpine *et. al.* 2009). Clearing of native vegetation, particularly for cattle grazing, is still underway.

NSW has recently changed its laws to facilitate widespread clearing of native vegetation. In recent decades dryland and irrigated agriculture that was traditionally concentrated in the intensive land use zone, has expanded into marginal semiarid regions of eastern Australia, increasing land clearance and demand on scarce water resources. Ongoing clearing has been offset to some extent by an increase in woody shrubs in grazing lands over recent decades.

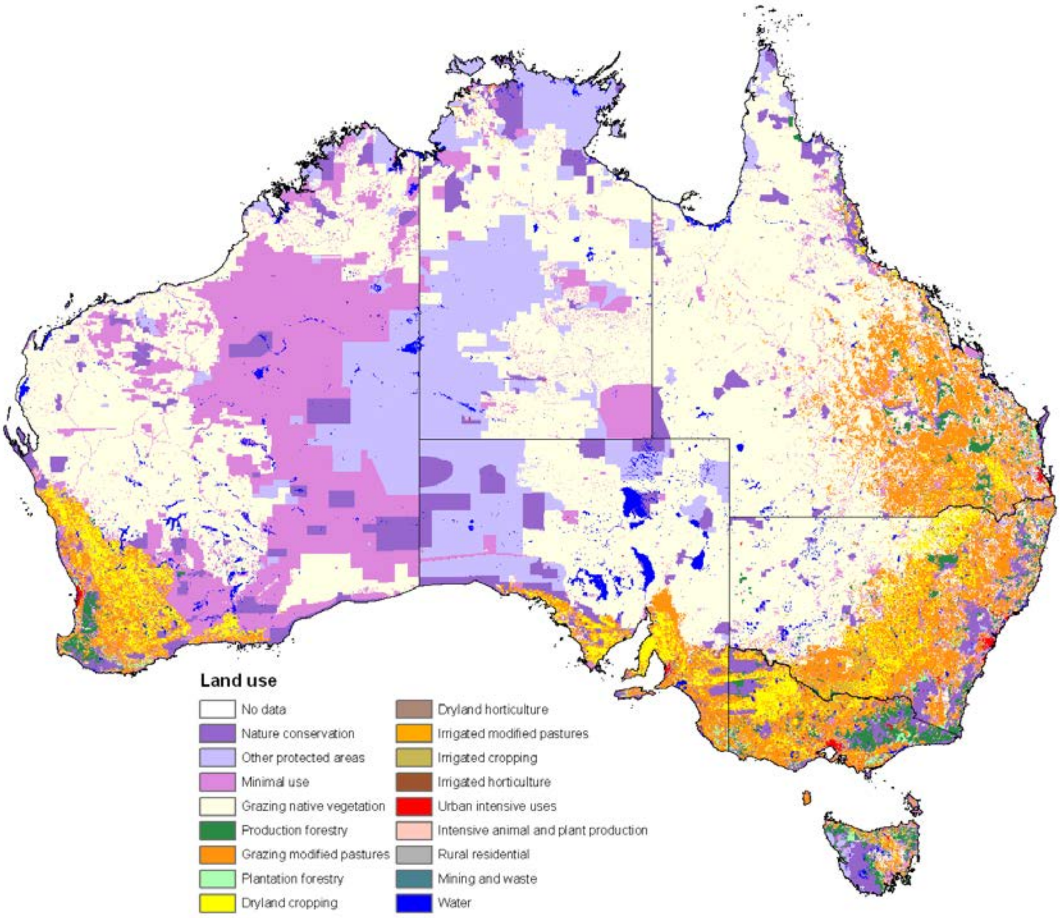


Figure 2. Land Use of Australia 2005-06, Version 4 (ABARE–BRS 2010)

Land use	Area(sq.km)	Percent (%)
Nature conservation	569,240	7.41%
Other protected areas including Indigenous uses	1,015,359	13.21%
Minimal use	1,242,715	16.17%
Grazing natural vegetation	3,558,785	46.30%
Production forestry	114,314	1.49%
Plantation forestry	23,929	0.31%
Grazing modified pastures	720,182	9.37%
Dryland cropping	255,524	3.32%
Dryland horticulture	1,092	0.01%
Irrigated pastures	10,011	0.13%
Irrigated cropping	12,863	0.17%
Irrigated horticulture	3,954	0.05%
Intensive animal and plant production	3,329	0.04%
Intensive uses (mainly urban)	16,822	0.22%
Rural residential	9,491	0.12%
Waste and mining	1,676	0.02%
Water	125,618	1.63%
No data	2,243	0.03%
Total	**7,687,147**	**100.00%**

Source: ABARE (2006).

Climate change is compounding the impacts of deforestation. Temperatures are rising. and over south-east and south-west Australia rainfall is declining, accordingly droughts in south-east Australia are intensifying with higher temperatures and prolonged heat waves.

There has been a decreasing trend in rainfall over much of southern and eastern Australia during the past 50 years, with strong seasonality and regional differentiations (Cai and Cowan 2008b, Speer *et. al.* 2011, Cai *et. al.* 2014). Speer *et. al.* (2011) identify that eastern Australia "*has experienced a decline in rainfall over the latter half of the twentieth century at a rate of between 30 and 50 mm per decade and 40–50 mm per decade since 1970*".

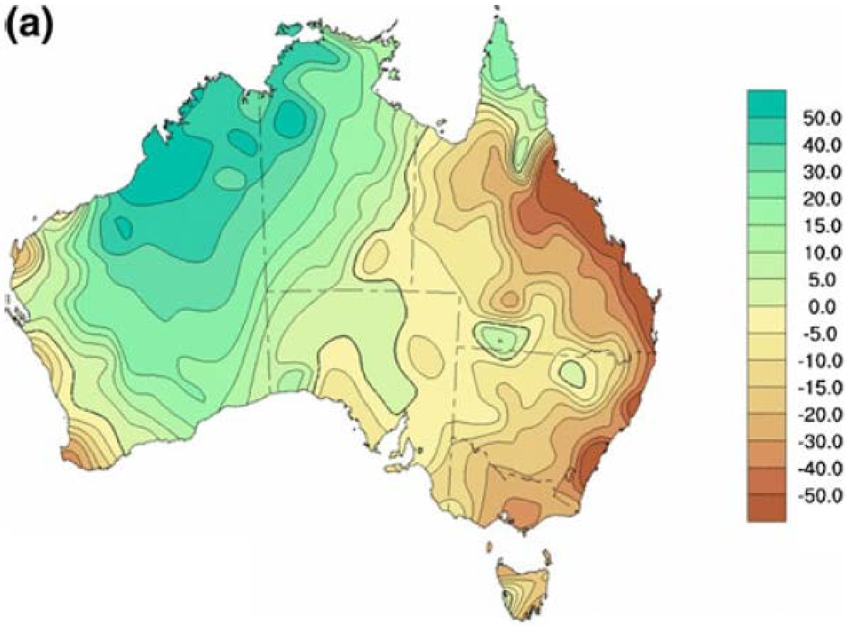


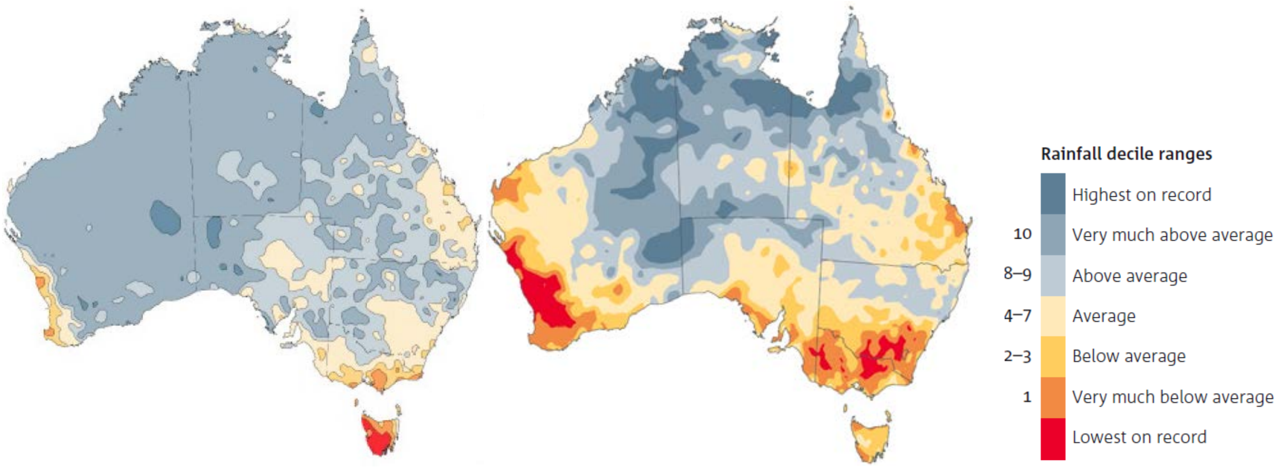
Fig. 1 from Speer *et. al.* (2011): Map of Australia highlighting the decline in annual rainfall (mm/10 years) around Australia from, 1950–2007.

Since the mid-to-late twentieth century there has been a prominent reduction in mid-to-late autumn rainfall over southeast Australia (Cai *et. al.* 2014). During 1950–2006, autumn rainfall over Victoria decreased by about 40% from its long-term seasonal average (Cai and Cowan 2008b). There has been a summer-autumn decline in rainfall over eastern Queensland of 20-30% (40–50% in coastal regions between Mackay and Townsville) since the 1950s (Cottrill 2009, Cai *et. al.* 2014). These rainfall declines have been characterised by step-wise seasonal reductions. The southern drying trends are characterised by a 10-20 percent reduction (expressed as a step change or series of step-changes) in cool season (April –September) rainfall across the south of the continent (Braganza *et al.* 2011). Significant rainfall declines have persisted since around 1970 in the south-west and since the mid-1990s in the south-east (Braganza *et al.* 2011). In south-west Australia there was an abrupt decline of around 14% in the mid 1970s (Bates *et. al.* 2008), since 1996 this decline from the long-term average has increased to around 25% (BoM 2016).

During the period between the mid-1990s and late 2000s, many Australian regions were plagued by concurrent severe droughts, which later became known as the Millennium Drought. This was the most severe drought experienced by southern Australia since instrumental record began in the 1900s (Cai *et. al.* 2014). Streamflows declined in a greater proportion than rainfall, as identified by CSIRO (2010) "*the 15 per cent reduction in rainfall during 1936-1945 led to a 23 per cent reduction in modelled annual streamflow in the southern Murray-Darling Basin ..., while the 13 per cent reduction in rainfall during 1997-2006 led to a streamflow decrease of 44 per cent*". From the late

1990's to 2001 there has been a major drop in streamflows into Perth's dams (Petrone *et. al.* 2010, Kinal and Stoneman 2012), causing the proportion of rainfall that became runoff to drop by an average 50%. In Western Australia this decline appears to be linked to the conversion of native forests to regrowth with higher evapotranspiration.

It appears that global warming was a contributing factor to the Millennium Drought but could not account fully for the severity of the drought (CSIRO 2010, Cai *et. al.* 2014). Cai *et. al.* (2014) compared the outcomes from the Millennium Drought with climate change models, concluding "*model results confirm that the drought over southern Australia is at least in part attributable to a recent anthropogenic-induced change in the climate ... despite models severely underestimating the magnitude of this shift. The changes in these climate indices are partially attributable to greenhouse warming ...*".



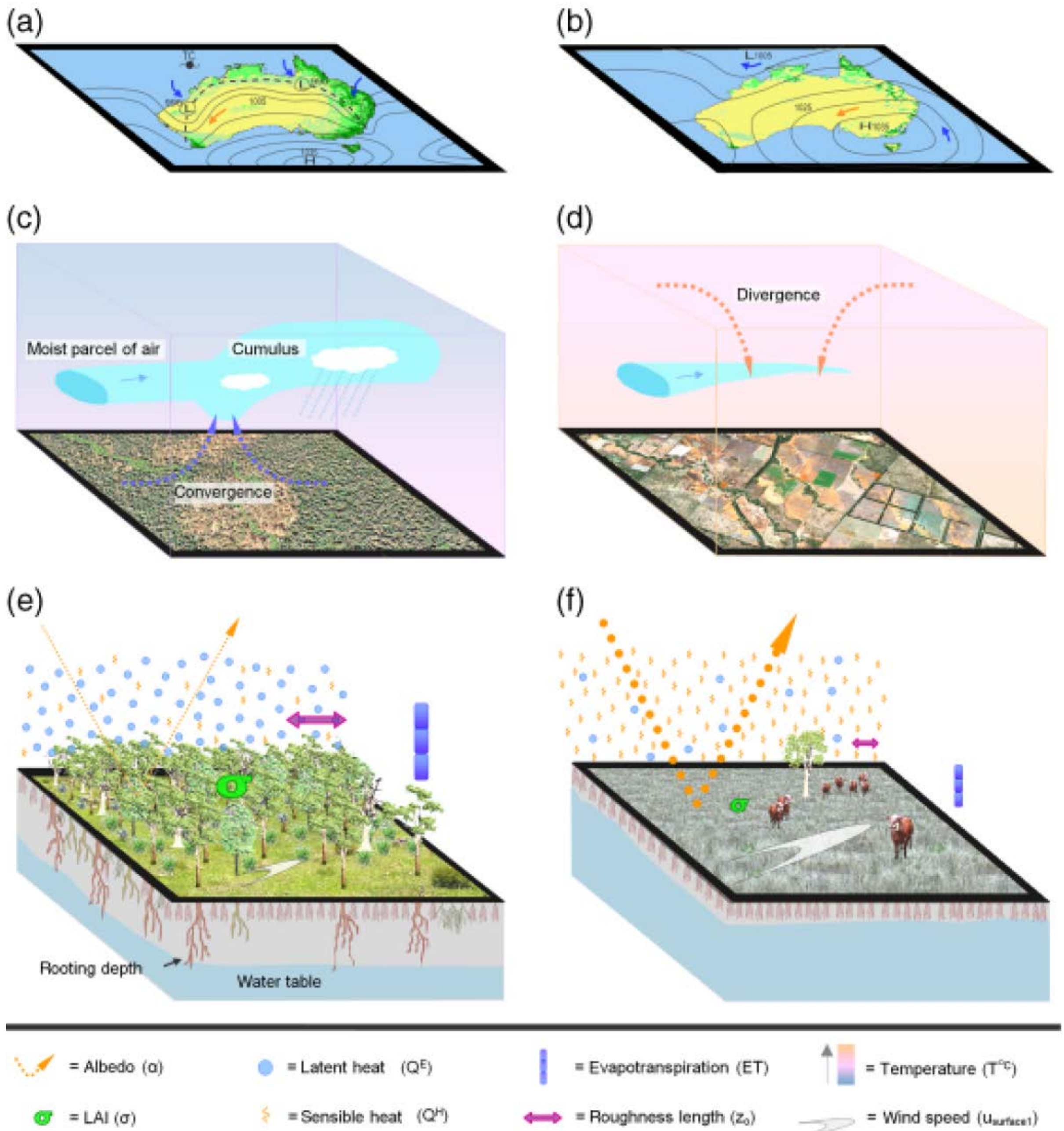
LEFT: Rainfall deciles for October-April 1997-2013 relative to 1900-2013. RIGHT: Rainfall deciles for April-September1997-2013 relative to 1900-2013 SOURCE: Braganza et. al. (2015). Note the striking correlations with the previous map of land uses, reflecting Land Cover Change.

Braganza *et. al.* (2015) consider that it has now been reasonably established that the decline in rainfall has been associated with both fewer rain-bearing systems, and less rainfall from those systems that do cross the region. Though the dynamics of this decline are poorly understood (Cai and Cowan 2008b). Speer et. al. (2011) consider the variability is partially related to long term climatic patterns: El Niño-Southern Oscillation (ENSO), the inter-decadal Pacific oscillation (IPO) and the southern annular mode (SAM). Cottrill (2009) linked rainfall declines in Queensland to mean sea level pressure, and changes in the 'subtropical ridge' and SAM, though recognised that deforestation played a part.

All the indications are that because of climate change, in southern and eastern Australia these trends of declining rainfall will continue (Bates *et. al.* 2008, Cai and Cowan 2008a, Mpelasoka *et.al.* 2007, CSIRO and Bureau of Meteorology 2015). Mpelasoka *et.al.* (2007) projected that "*by 2030, soil-moisture-based drought frequency increases 20–40% over most of Australia with respect to 1975–2004 and up to 80% over the Indian Ocean and southeast coast catchments by 2070*". Based on CSIRO and Bureau of Meteorology (2015) climate change projections:

- in southern mainland Australia, winter and spring rainfall is highly likely to decrease, possibly by as much as 50% in south-west Western Australia by 2090
- it is likely that rainfall will decrease in south-western Victoria in autumn and in western Tasmania in summer
- for eastern Australia it is likely that winter rainfall will decrease by 2090

- it is highly likely that extreme rainfall events will increase in intensity, except possibly in south-west Australia
- the frequency and intensity of droughts are likely to increase, particularly in southern Australia.



A schematic model from McAlpine *et. al.* (2009) showing the effect of land cover change on the boundary layer properties at the continental scale (a, b), regional scale (c, d) and landscape scale (e, f). The models on left show intact Australian native woodlands, models on the right show feedbacks following clearing. At landscape scale, the major transformations (e > f) include increased sensible heat flux, albedo, and wind speeds. The leaf area index (LAI), vegetation fraction, evapotranspiration, latent heat flux, surface roughness and soil moisture have decreased. At the regional scale, these changes in fluxes alter the feedbacks to broader exchange of moisture between the land surface and the boundary layer, and regions of forced convection and advection (c > d), which in many cases have contributed to decreases in cumulus cloud formation. The potential for cumulative effects of regional changes in land cover on pressure systems are shown schematically as D isobars (a > b). Artwork by Justin Ryan.

While climate change due to increasing atmospheric CO^2 appears to have been a significant factor in rainfall declines, there is growing evidence that land use change has played a major role. The co-incidence of rainfall decline with land clearing is unlikely to be due to chance.

Gordon *et. al.* (2003) estimate that shift in Australia land use from 1780 to 1980 resulted in the conversion of around $80x10^6$ ha of woody vegetation (wet dense forest, open forest, woodland) to grassland/croplands, causing in the order of a 10% decrease in water vapour (evapotranspiration) flows, which corresponds to an annual freshwater flow of almost 340 km^3, or "*more than 15 times the volume of run-off freshwater that is diverted and actively managed in the Australian society*".

Narisma and Pitman (2003) undertook modelling to identify the likely consequences of changes between natural (1788) and current (1988) vegetation cover, considering reduced evaporation was the main influence that explained the reduced rainfall, and noting:

> *Results show that the impact of land cover change on local air temperature is statistically significant at a 99% confidence level. Furthermore, there are indications that the observed increase in local maximum air temperatures in certain regions of Australia can be partially attributed to land cover change. The results are evidence of statistically significant changes in rainfall, and the sign of these changes over Western Australia in July, and the lack of any simulated changes in January, agree with observations. These results provide further evidence of large-scale reductions in rainfall following land cover change. Changes in wind speed are also simulated and are consistent with those expected following land cover change. The results indicate that attempts to identify greenhouse-related warming in Australian air temperature records should account for the effects of both land cover change and increasing CO^2 concentrations since both types of anthropogenic forcing exist in long-term observational records.*

Syktus *et.al.* (2007) undertook a comparison of pre-European and modern day land surface parameters, identifying that due to land cover change average rainfall decreased by 2.5% in Queensland, 5.2% in eastern New South Wales/Victoria and 0.9% in south-western Australia, summarising their findings:

> *... an increase in albedo for all regions were land cover change had occurred. ... increased strength of surface winds by reducing aerodynamic drag ... modified surface evaporation, latent and sensible heat fluxes and planetary boundary layer properties ...The increase in near surface wind amplified the shift from moist northeast tropical air to cooler and drier southeast flow from the Tasman Sea, resulting in the decreased rainfall. Results showed that the regional perturbation of vegetation can possibly magnify the impact of natural mode of individual El Niños, which together with rainfall deficiency, could have a strong impact on climate conditions (e.g. droughts) in eastern Australia. Hence, the replacement of native vegetation with seasonal cropping and improved pastures is likely to be contributing to more severe droughts and increased demand for water.*

McAlpine *et. al.* (2007) undertook modelling to compare the effects on Australian climate based on differences between pre-European and 1990 vegetation cover, finding:

> *Consistent with actual climate trends since the 1950s, simulated annual and seasonal surface temperatures showed statistically significant warming for eastern Australia (0.4-2°C) and southwest Western Australia (0.4-0.8°C), being most pronounced in summer. Mean summer rainfall showed a decrease of 4-12% in eastern Australia and 4-8% in southwest Western Australia which coincided with regions where the most extensive land clearing has occurred.*

Further, the study found an increase in temperatures on average by 2°C, especially in southern Queensland and New South Wales, for the recent 2002/2003 drought.

The findings suggest that the large scale clearance of native vegetation is amplifying the adverse impacts associated with El Niño drought periods, which together with rainfall deficiency, is having a strong impact on Australia's already stressed natural resources and agriculture.

Based on McAlpine *et. al.* (2007) and Syktus *et.al.* (2007), McAlpine *et. al.* (2009) derived regionally averaged values of mapped surface parameters for pre-European and modern-day land cover characteristics and the corresponding changes in regional climate over eastern New South Wales in summer, identifying:

During the summer season in eastern New South Wales, the area-averaged changes in surface characteristics (Fig. 5a) showed large decreases in vegetation fraction (19%) and LAI [leaf area index] (23%), and a resulting 7% increase in albedo. A corresponding reduction in surface roughness (46%) coincided with a 9% increase in wind speed, while summer surface temperatures exhibited an average warming of [approx.] *0.6°C. This warming was related to an increase in surface absorption of incoming short-wave radiation by 5.2%. The area-averaged rainfall decreased by 5.2%. The area-averaged energy fluxes showed a reduction in latent heat flux (7.3%) and an increase in sensible heat flux (1.3%).*

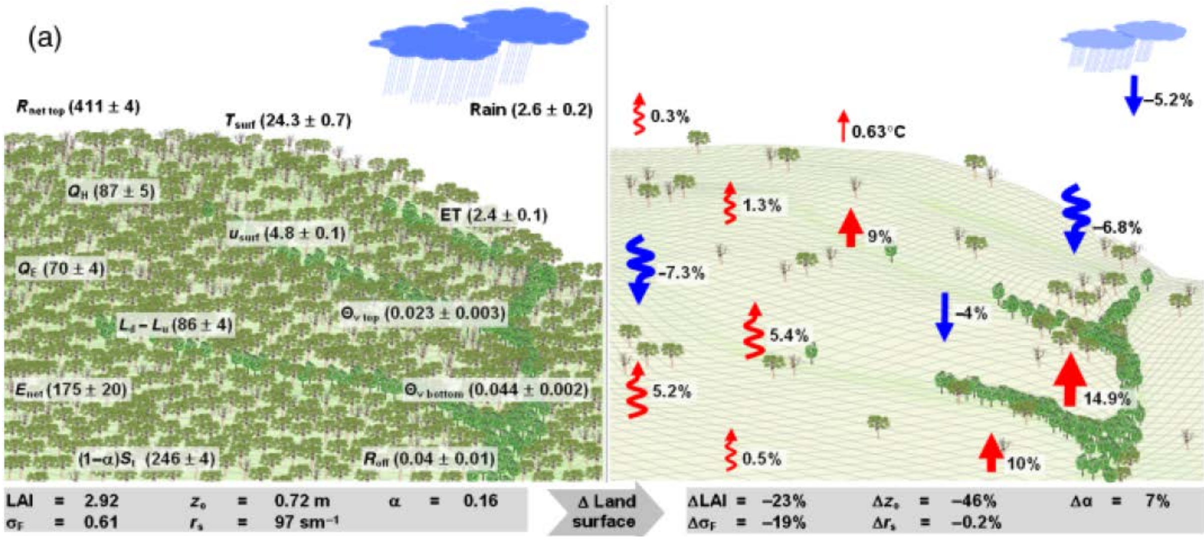


Fig. 5 from McAlpine *et..al.* (2009) showing a hypothetical ecosystem in the Australian summer for eastern New South Wales, both pre-European and today. LEFT: a pre-clearing (natural) ecosystem with the initial land surface properties/fluxes with natural vegetation (bottom box) and corresponding climate responses (labels on landscape model); RIGHT: changes in land surface properties/fluxes due to clearing (bottom box) and corresponding climate responses (labels on landscape model) in a present-day-modified landscape. Note: blue arrows (decreases), red arrows (increases), arrow width relative to magnitudes of change. a, surface albedo; LAI, leaf area index; sF, vegetation fraction; z0, surface roughness; rs, stomatal resistance; Tsurf, surface temperature; Rain, rainfall; QH, sensible heat flux; QE, latent heat flux; Ld_Lu, net surface long-wave radiation; (1_a)St, net surface short-wave radiation; Enet, net surface energy; Rnet top, net radiation at top of atmosphere; usurf, surface windspeed; (yv top , Yv bottom), top and bottom layer soil moisture and ET, evapotranspiration rates. Artwork by Justin Ryan.

McAlpine *et..al.* (2009) summarise:

> *The historical clearing of approximately 15% of the continent for agriculture is likely to have contributed to a hotter and drier climate and exacerbated the effect of the El Niño by increasing the severity of droughts, especially in south-east Australia. This problem is being compounded by the interaction of contemporary land use pressures and an emerging trend towards a hotter and more-drought-prone climate driven by increased anthropogenic greenhouse gases.*

Deo *et.al.* (2009) modelled the consequences of land cover change (LCC) for the period 1951–2003 to quantify the impact of LCC on selected daily indices of climate extremes, finding:

> *The results showed: an increase in the number of dry and hot days, a decrease in daily rainfall intensity and wet day rainfall, and an increase in the decile-based drought duration index for modified land cover conditions. These changes were statistically significant for all years, and especially pronounced during strong El Niño events. Therefore it appears that LCC has exacerbated climate extremes in eastern Australia, thus resulting in longer-lasting and more severe droughts.*

As noted by Deo (2011)

> *Clearly, these studies have demonstrated that LCC has exacerbated the mean climate anomaly and climate extremes in southwest and eastern Australia, thus resulting in longer-lasting and more severe droughts.*

In relation to 'land use/land cover change' (LUCC) McAlpine *et. al.* (2009) warn:

> *The consequences of ignoring the effect of LUCC on current and future droughts in Australia could have catastrophic consequences for the nation's environment, economy and communities. We highlight the need for more integrated, long-term and adaptive policies and regional natural resource management strategies that restore the beneficial feedbacks between native vegetation cover and local-regional climate, to help ameliorate the impact of global warming.*

McAlpine *et. al.* (2009) emphasise:

> *Reducing greenhouse gas emissions is essential but not sufficient as a climate change mitigation strategy. Anticipatory policies need to be explored and tested aiming at reduction in land use pressures and restoration of native vegetation cover in order to try to avoid likelihood of irreversible climate change. Potential mitigation and adaptation options include: (1) tighter legislative controls on the clearing of native vegetation, including regrowth native vegetation in previously cleared subtropical landscapes; (2) expanded investment in ecological restoration based on the strategic integration of native vegetation with production systems in the highly modified agricultural landscapes; (3) an evaluation of the long-term viability of marginal cropping and grazing lands and their vulnerability to soil and vegetation degradation; and (4) adaptive management of stocking rates according to climate conditions.*

2.3. Groundwater-Associated Salinity

Over many thousands of years, salt has been accumulating in Australian soils delivered by wind and rain from the sea, or left-over from ancient inland seas. The minimal runoff has allowed the salts introduced through rainfall or rock weathering to build up in the soil below the depth of plant roots. Williams *et. al*. (2002) consider:

> *It is well documented that healthy native ecosystems within catchments are in hydraulic and salt balance ... The input of salt to the catchment is balanced by the salt discharged from the*

> *catchment. Once clearing occurs and a agriculture is introduced, the salt discharged from the catchment begins to greatly exceed the salt entering the catchment.*

Rengasamy (2006) observes:

> *Under native vegetation, leaching of salts from the permeable soil due to natural processes led to salt storage in deep regolith or the accumulation of salts in the shallow groundwater. ... As long as the water table was 4 m below the surface, saline groundwater did not affect native vegetation while some species could cope with shallower water tables.*

One of the principal impacts of deforestation is the raising of groundwater levels. Rising groundwaters can be problematic where aquifers have been disconnected from throughflows and have thus accumulated salts. The total salinity and the composition of many saline groundwater samples in Australia are similar to seawater. Salinisation of land is not a new problem, in southern Mesopotamia and in several parts of the Tigris–Euphrates valley it destroyed the ancient societies that had successfully thrived for several centuries (Rengasamy 2006). Salinisation was recognised as a potential problem as early as 1864 in Western Australia and the hydrological factors responsible were identified in 1897. The major attention for salinity in Australia is on irrigation-induced salinity in the Murray-Darling basin and dry-land salinity associated with shallow groundwater, particularly in Western Australia (Rengasamy 2006).

Groundwater-associated salinity is a form dry-land salinity resulting in the visual scalding of soil surfaces, usually at the foot of slopes and in valley floors, associated with a rising saline water table. The clearing of woody vegetation reduces the rooting depth of vegetation and evapotranspiration, the reduced transpiration of deeper soil moisture can allow water-tables to rise, in places allowing saline watertables to rise to the surface and enter streams (Allison *et. al.* 1990, Ruprecht and Schofield 1991a, NLRWA 2001, Williams *et. al*. 2002, Gordon *et. al.* 2003, Silberstein *et. al.* 2003, Bari and Ruprecht 2003, Hatton *et. al.* 2003, Rengasamy 2006).

Salinisation is generally a problem of lower rainfall areas, as noted by Bari and Ruprecht (2003):

> *The permanent groundwater system in the high rainfall areas (annual rainfall above 1100 mm) usually discharges to streams and keeps these areas leached of salt. As such, the high rainfall areas are generally of low salinity hazard. In the low rainfall areas, the deep groundwater tables are far below the stream bed and do not contribute to streamflow. As a consequence, salt has accumulated in the unsaturated zone and these areas pose a high potential salinity hazard. ...*

Silberstein *et. al.* (2003) describe the process of dryland salinity:

> *However, clearing of the native vegetation since European settlement has tipped over this delicate balance and caused increased recharge, which led to rapid rise in groundwater tables and increased groundwater discharge to streams.*
>
> *...*
>
> *When the watertable rises the salt is dissolved. This groundwater flow carries huge quantities of salt to the surface, discharging to streams and concentrated by evaporation, causes large scale land and stream degradation.*
>
> *...*
>
> *As a result of the shallower saline watertables, evaporation at the soil surface brings salt to the surface through capillary rise, and accumulates in large white crusted salt scalds. When rain falls the surface accumulations of salt wash off and are rapidly transported to the*

stream. Additionally, the shallow watertable means that the infiltration capacity of catchments is reduced and the runoff/rainfall ratio increased.

Hatton *et. al.* (2003) summarise the experience in south-western Australian:

The hydrological and hydrogeochemical changes induced by widespread clearing of this vegetation for dryland agriculture are profound and enduring. Run-off onto and through the valley floors has increased by a factor of five; combined with local rainfall on these valley floors, the resulting increase in groundwater recharge is filling the deep sedimentary materials and bringing highly saline water to the surface. Diffuse recharge has also increased on the slopes and ridges, with saline watertables rising in these lateritic formations as well, providing additional hydraulic heads forcing groundwater towards the valleys.

Ruprecht and Schofield (1991a, b) partially deforested (western 53% of the catchment) a small (344ha) experimental catchment in southwest Western Australia in 1976 to study the effects of agricultural development on water quantity and quality, finding:

However, since 1987, stream salinity increased dramatically as the ground water approached the ground surface, and by 1989 reached an annual average of 290 $mgl^{-1}Cl^{-}$. The daily maximum in 1989 was 2200 $mgl^{-1}Cl^{-}$ compared with 92 $mgl^{-1}Cl^{-}$ from 1976 to 1986. The catchment changed from net salt accumulation pre-clearing to net salt export after 1987. Thirteen years after clearing, the groundwater level, stream yield, stream salt load and stream salinity had not reached equilibrium but were all still increasing

Bari and Ruprecht (2003) further document the salinity problem:

Salt storage in the soil profile at the Wights and Lemon catchments is 0.4 kg/m^2 and 2.3 kg/m^2 respectively (Johnston 1987; Bari et al. 2003). The annual stream salinity at the Wights catchment increased immediately after clearing from an average of 360 to 515 mg/L TDS (Fig. 9). The average annual salt load increase at the Wights catchment was 14-fold (compared with the control catchment). At the Lemon catchment, from 1977–87 (before the groundwater system was connected to the streambed), the average annual stream salinity rose from 80 to 127 mg/L TDS. After 1987 when the groundwater system reached the streambed, the stream salinity generation process changed significantly and annual average salinity increased systematically to 1700 mg/L TDS. The annual stream salt load increased 180-fold compared with the control catchment.

To date, salinisation in southern Australia has generally been limited to areas where ground water was originally relatively near the land surface, though in areas with low rainfall and deep groundwaters it can take tens or hundreds of years for saline groundwater to rise to the surface, so there are many areas where the impacts of clearing undertaken decades ago are yet to materialise. From their study of land clearance and river salinisation in the western Murray basin, Allison *et. al.* (1990) concluded:

Rates of groundwater recharge under native mallee vegetation in the western Murray Basin are less than 0.1 mm $year^{-1}$. After clearing, the mean recharge rates increase by approximately two orders of magnitude to between 5 and 30 mm $year^{-1}$. The water table over much of the western Murray Basin occurs more than 30 m below the land surface, and this, coupled with the low rates of recharge, results in a considerable delay in the response of the aquifer to the increased recharge. ... The development of land salinisation has thus been slow, and restricted to areas where the water table was initially within only a few metres of the ground surface.

> *... The increased inflow of saline water to the River Murray will cause its salinity to steadily increase over at least the next 200 years unless a combination of land management and engineering strategies is adopted.*

The National Land and Water Resources Audit (NLRWA 2001) identifies that recent estimates indicate that *ca*. 5.7 million hectares of Australia are currently at risk of dryland salinity, which could rise to over 17 million hectares by 2050. Western Australia is the worst off with 33% of the land area at risk of salinisation, followed by Victoria.

Williams *et. al*. (2002) consider that "*Dryland salinity is undoubtedly the greatest and most intractable threat to the health and utility of Australia's rivers, soil and vegetation ... if we do not find and implement effective solutions, the area of land affected by dryland salinity is likely to rise to between 10 and 12 million ha over the next fifty years*", noting:

> *Western Australia has the greatest area of dryland salinity at present (1.8 million ha) with the potential to rise to 6.1 million ha; all the rivers of south-western Western Australia are salinised or salinising. A similar picture is emerging for South Australia, where Jolly et al. (2000a) showed that all surface waters are either salinised or at risk of serious salinisation. New South Wales is of critical concern, with 7.5 million ha potentially at risk*

Gordon *et. al.* (2003) identify that "*production loss due to saline river water, health hazards, deterioration of agricultural lands, destruction of infrastructure in rural and urban areas, and loss of biodiversity and ecosystem services in both terrestrial and aquatic environments are among the social costs*" of dryland salinisation.

As salinisation develops it kills the affected vegetation, creating a positive feedback that helps perpetuate the problem.

The salinisation of the landscape resulting from deforestation provides a clear and urgent reason to stop land clearing in any landscapes where there is a risk of this occurring. While considerable effort has gone into identifying such areas, they do not appear to be off-limits for further deforestation.

2.4. The Western Australia Experience

The effects of deforestation in south-west Western Australia (SWWA) on streamflows have been extensively studied because the vegetation has been finely balanced with rainfall, using most of the available rainfall and leaving little excess for stream flow. The region is used in this review as a case study of the problems being experienced across southern and eastern Australia as a result of deforestation and land degradation.

SWWA can be defined as a 25,000 km^2 coastal plain (the coastal strip) stretching 500 km from north to south and 30-100 km wide. Flanked to the east by 300-500 m high hills (the Darling scarp) with a large flat plain 300 m above sea level that covers 171,000 km^2 to the northeast (the wheatbelt). This is separated from land that is too dry for agriculture (the goldfields) to the east by the rabbit fence. In SWWA almost all of the rain consistently arrives during the months of April to October brought on by cold fronts moving west from the Indian Ocean over the coast. (Andrich and Imberger 2013)

Deep groundwater supplies have been crucial in maintaining tree transpiration during the severe dry periods that are often experienced. Silberstein *et. al.* (2003) identify that "*prior to clearing for agriculture the deep rooted perennial native vegetation used virtually all the available rainfall, and maintained a very deep or non-existent watertable. What little groundwater flow there was, was very slow due to the low gradients and low transmissivities*". Silberstein *et. al.* (2001) observe "*the jarrah (Eucalyptus marginata) forest in southwest Western Australia is capable of maintaining vigorous growth through severe dry summers, during which there may be little or no rain for close on 6 months. in part because they can access the deep soil water to maintain high evaporation rates in the summer months and avoid significant water stress*".

Hatton *et. al.* (2003) summarise the south-western Australian experience with widespread clearing:

> *The accumulation and distribution of salt, the rudimentary aquifers with deep watertables, the intermittent flooding and subsequent transpiration of water from the valley sediments, and the low yields of water reaching the ocean were a product of the underlying physical environment and vegetation types capable of using deeply infiltrated water through the dry season. The hydrological and hydrogeochemical changes induced by widespread clearing of this vegetation for dryland agriculture are profound and enduring. Run-off onto and through the valley floors has increased by a factor of five; combined with local rainfall on these valley floors, the resulting increase in groundwater recharge is filling the deep sedimentary materials and bringing highly saline water to the surface. Diffuse recharge has also increased on the slopes and ridges, with saline watertables rising in these lateritic formations as well, providing additional hydraulic heads forcing groundwater towards the valleys.*

In the mid-1970s Southwest Western Australia (SWWA) experienced a step-wise change in climate manifesting itself as a rapid 15–20% decrease in rainfall and an associated >50% decrease in runoff into Perth's drinking water catchments (Bates *et. al.* 2008, Petrone *et. al.* 2010). Since 1996 this decline in rainfall from the long-term average has increased to around 25% (BoM 2016). From the late 1990's to 2001 there was a major drop in streamflows into Perth's dams (Petrone *et. al.* 2010, Kinal and Stoneman 2012), causing the proportion of rainfall that became runoff to drop by an average 50%.

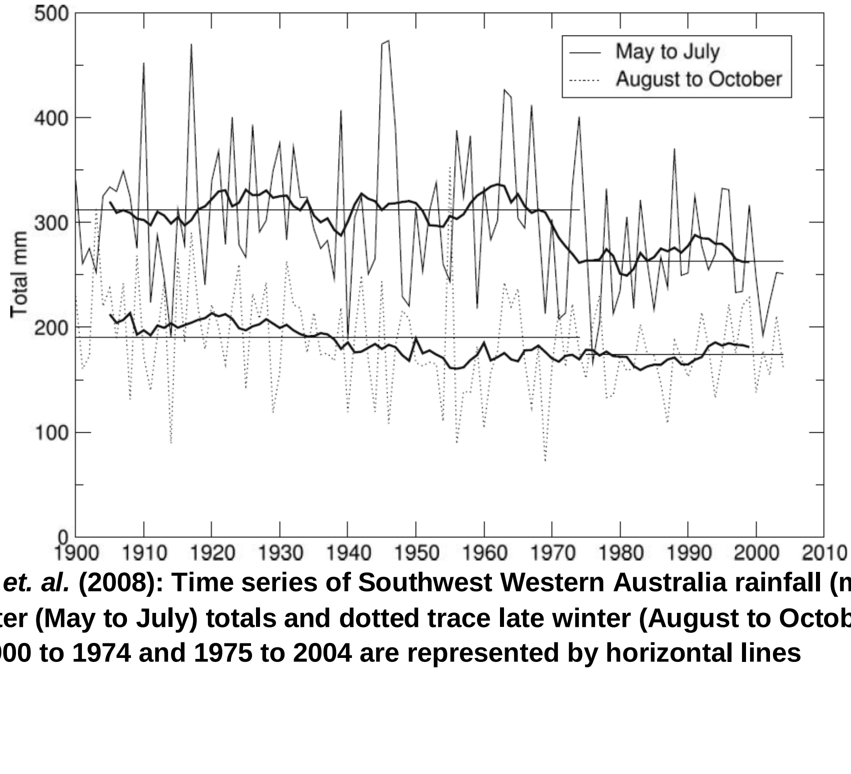


Fig. 4 from Bates *et. al.* (2008): Time series of Southwest Western Australia rainfall (mm). Solid trace depicts early winter (May to July) totals and dotted trace late winter (August to October) totals. Means for the periods 1900 to 1974 and 1975 to 2004 are represented by horizontal lines

Ongoing declines in streamflows, and tree deaths due to apparent water stress in the *Eucalyptus gomphocephala* (Tuart) forest in southern SWWA and *Eucalyptus wandoo* woodland in eastern SWWA, have heightened concern that the rainfall decline is intensifying (Bates *et. al.* 2008). Climate models suggest that rainfall in the region will go on declining, and evaporation increase, as the earth warms (Bates *et. al.* 2008).

This abrupt decline in rainfall has been partially attributed to a poleward shift of the extratropical jet resulting in a decrease of westerly winds bringing less rainfall over land (i.e. Bates *et. al.* 2008), though other studies "*suggest that effects of land cover change (LCC) may also be substantial and this has been confirmed by modeling studies*" (Nair *et. al.* 2011). Andrich and Imberger (2013) compiled rainfall and clearing records for SWWA, considering that the "*data do not support the hypothesis that global warming has shifted rain bearing cold fronts southward*", and that "*natural variation and global warming may be contributing at most to a combined 12.5% decline in rainfall*".

By 1950, 30% (68,000 km^2) of the SWWA arable area had been cleared. From 1950 to 1980, 42% of SWWA land (82,000 km^2) was cleared with the introduction of new machinery and active government promotion of large-scale clearing. Between 1980 and 2000 the rate of land clearing slowed with 4% (9,000 km^2) of native vegetation cleared. By 2002 dryland salinity was recognized to affect over 5,000 km^2 of previously productive agricultural land. (Andrich and Imberger 2013).

From their comparison of land clearing and rainfall records Andrich and Imberger (2013) found that "*deforestation causing native vegetation to reduce from 60% to 30% of the coastal strip correlates with a 15.2% to 18% decline in annual winter rainfall (relative to rainfall at the coast)*", concluding *"that 50-80% of the 30% rainfall decline observed since 1970 could be attributed to land-use change".*

Pitman *et.al.* (2004) undertook modelling to assess the likely contribution of Land Cover Change (LCC) to the declining rainfall, concluding:

> *We find that land cover change explains up to 50% of the observed warming. Following land cover change, we also find, in every simulation, a reduction in rainfall over southwest Western Australia and an increase in rainfall inland that matches the observations well. We show that the reduced surface roughness following land cover change largely explains the simulated changes in rainfall by increasing moisture divergence over southwest Western Australia and increasing moisture convergence inland. Increased horizontal wind magnitudes and suppressed vertical velocities over southwest Western Australia reduce the likelihood of precipitation. Inland, moisture convergence and increased vertical velocities lead to an increase in rainfall. Our results indicate that rainfall over southwest Western Australia may be returned to the long-term average through large-scale reforestation, a policy option within the control of local government.*

Timbal and Arblaster (2006) undertook modelling that also indicated Land Cover Change is likely to be a significant contributor to the declining rainfall:

> *We found that vegetation cover affects modelled rainfall in the region and enhances the model response to anthropogenic atmospheric forcings (including greenhouse gases, ozone and sulphate aerosols), which were found in a previous study to explain part of the observed rainfall decline. ... While the rainfall response to anthropogenic forcings is driven mostly by the changes in pressure, the land cover influences directly the modelled rainfall (large-scale and total) and thus indirectly the downscaled rainfall. A plausible trigger appears to be the reduction of roughness length.*

Kala *et. al.* (2011) modelled a summer and a winter cold front in SWWA to assess the impacts of land clearing, and:

> *found that land-cover change results in a decrease in precipitation for both fronts, with a higher decrease for the summer front. The decrease in precipitation is attributed to a decrease in turbulent kinetic energy and moisture flux convergence as well as a increase in wind speed within the lower boundary layer. The suggested mechanism is that the enhanced vertical mixing under pre-European vegetation cover, with the decrease in wind speeds close to the ground, enhance microphysical processes leading to increased convective precipitation. The higher decrease in precipitation for the summer front is most likely due to enhanced convection during summer.*

Many authors have taken advantage of a 750 km rabbit-proof fence in south-western Australia that separates 13 million hectares of croplands from the remnant native vegetation to the east to assess climatic changes across the boundary. The problem is that the fence is the divide between land suitable for agriculture from land too dry for agriculture, with most vegetation to the east of the fence 0.5 m and 2.0 m high. They have all observed preferential cloud formation over native vegetation compared to the croplands (Huang *et. al.* 1995, Lyons 2002, Junkermann et.al. 2009, Nair et. al. 2011). The groundwater table in the agricultural region rose from >20m deep to around 2m within 30 years since 1950 with a concurrent increase in groundwater salinity (Junkermann et.al. 2009).

Huang *et. al.* (1995) considered "*that convective mixing over the cleared land is no longer able to reach the lifting condensation level for a significant period of the year. This implies a decrease in convective cloud formation and a reduction in the convective enhancement of rainfall*".

Lyons (2002) considered "*that the darker albedo of the native vegetation provided that local forcing to assist in convective development over the native vegetation in contrast to the lack of development over the agricultural land. Thus changes in the surface albedo through clearing for agriculture have decreased the local forcing necessary to trigger storm development*".

Junkermann *et.al.* (2009) found:

> *Besides different meteorology, we found a significant up to now overlooked source of aerosol over the agriculture area. The enhanced number of cloud condensation nuclei is coupled through the hydrological groundwater cycle with deforestation. Modification of surface properties and aerosol number concentrations are key factors for the observed reduction of precipitation.*

Nair *et. al* (2011) considered the primary cause for rainfall decrease in the area subject to Land Cover Change (LCC) is due to changes in low-level convergence, caused by alteration of both west coast trough dynamics and aerodynamic roughness, noting:

> *Observations and numerical model analysis show that the formation and development of the west coast trough (WCT), which is a synoptic-scale feature that initiates spring and summertime convection, is impacted by land cover change and that the cloud fields induced by the WCT would extend farther west in the absence of the LCC. The surface convergence patterns associated with the wintertime WCT circulation are substantially altered by LCC, due to changes in both WCT dynamics and surface aerodynamic roughness, leading to a rainfall decrease to the west of the rabbit fence.*

Studies in 27 experimental catchments in the south–west of Western Australia examined the impacts of land use practices such as clearing for agricultural development, forest harvesting and regeneration, forest thinning, bauxite mining and reforestation on water yields to streams (Bari and Ruprecht 2003). They found that clearing led to permanent increases of water yield of about 30% of annual rainfall for high rainfall (1100 mm mean annual rainfall) and 20% of annual rainfall for low rainfall areas (900 mm annual rainfall). Logging, thinning and reafforestation of mines led to initiation of regrowth with increasing evapotranspiration.

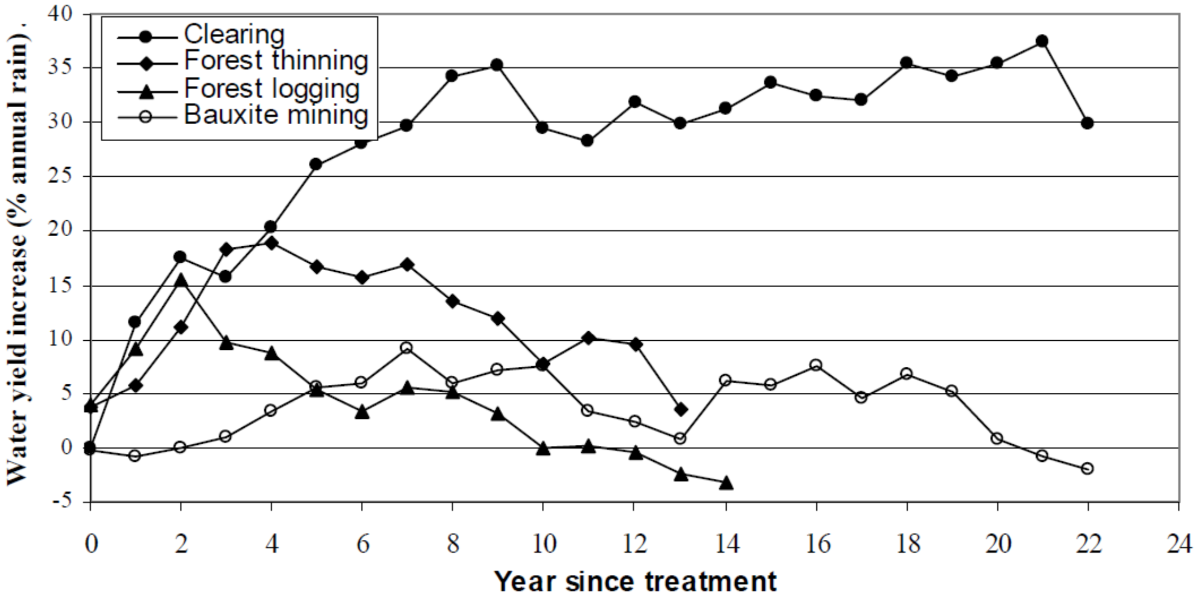


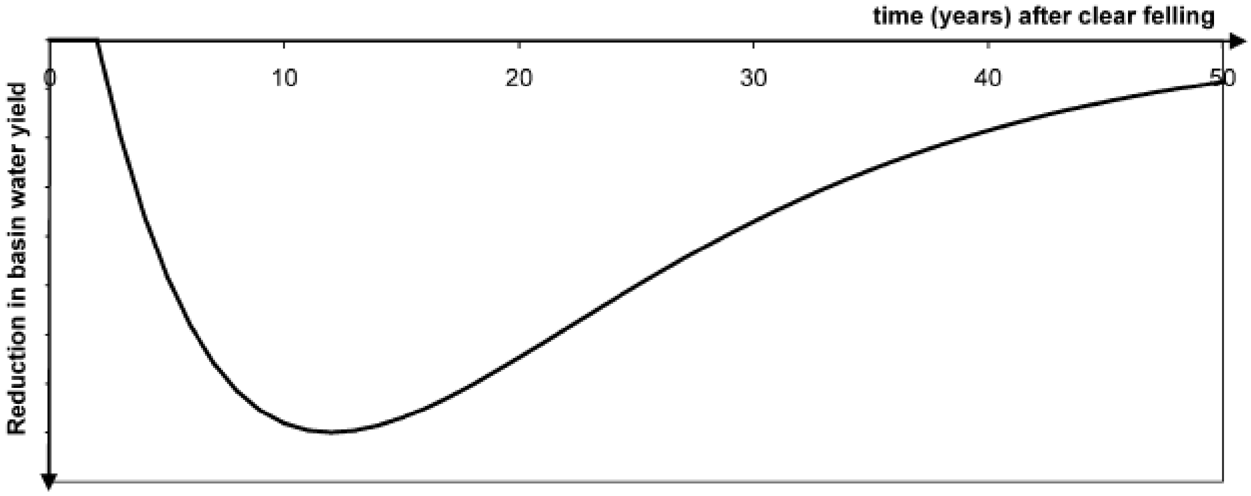
Figure 19 from Bari and Ruprecht (2003): Comparison of stream yield responses to land use practices in the south-west Australian 'High Rainfall Zone'.

From their assessment of these catchments Silberstein *et. al.* (2003) identify:

> *The proportion of rainfall that becomes stream flow (runoff coefficient) has increased as a response to clearing, and continued to increase through time in the cleared catchments ...*
>
> *For all occurrence frequencies there is more flow in the cleared catchments and much fewer days without flow than in the catchments still forested over the same time period. These trends increase in time. ...*
>
> *Following clearing, runoff coefficient has risen by a factor of 5 in the wetter catchments, about 10-20 in the intermediate catchments, and up to 100 times in the drier catchments, which have almost no runoff under natural conditions. ...*

While the evidence is that permanent clearing of native vegetation results in an increase in runoff to streams, which can largely be attributed to a reduction in evapotranspiration, it is equally clear that activities such as logging and thinning can result in reduced runoff over time. The generalised pattern following heavy and extensive logging of an oldgrowth forest is for there to be an initial increase in runoff peaking after 1 or 2 years and persisting for a few years. Water yields then begin to decline below that of the oldgrowth as the regrowth uses more water. Water yields are likely to reach a minimum after 2 or 3 decades before slowly increasing towards pre-logging levels in line with forest maturity. (Kuzcera 1987, Vertessy *et. al.* 1998, Cornish and Vertessy 2001, Bari and Ruprecht 2003, Brown *et. al.* 2005, Burrows *et. al.* 2011).

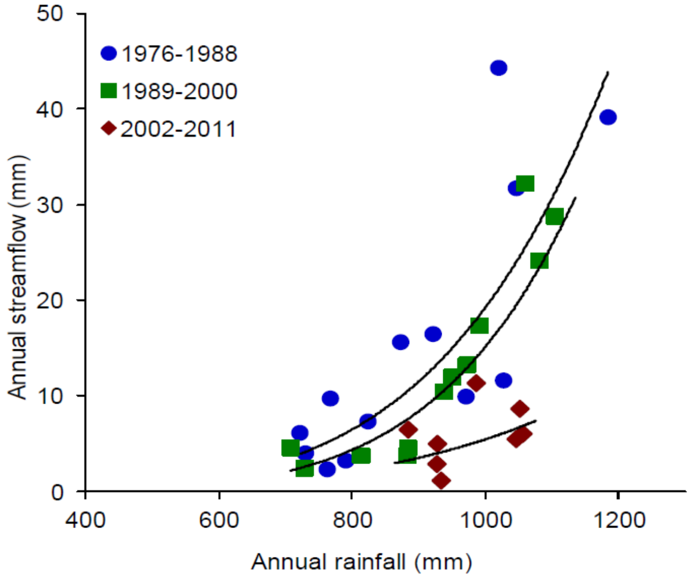
Kuczera (1985, cited in Vertessy *et. al*. 1998) developed an idealised curve describing the relationship between mean annual streamflow and forest age for mountain ash forest in Victoria. This shows that after burning and regeneration the mean annual runoff reduces rapidly by more than 50% after which runoff slowly increases along with forest age, taking some 150 years to fully recover.



Kuczera (1985) Curve.

In the western Australian catchments Bari and Ruprecht (2003) found logging and thinning led to increases in runoff for 10-15 or more years, with maximum increases ranging from 5 to 19% of mean annual rainfall, depending on the level of reduction of vegetation cover and catchment characteristics. As indicated by the trends, stream flows are likely to have continued to decline because of the increasing evapotranspiration of the regrowth.

From the late 1990's to 2001 there has been a major drop in streamflows into Perth's dams (Petrone *et. al.* 2010, Kinal and Stoneman 2012) which has been attributed to a disconnect between groundwater and stream flows. Kinal and Stoneman (2012) identified that from 1976 to 2011 the groundwater system progressively declined and disconnected from the surface water system around 2001, causing the proportion of rainfall that became runoff to drop by an average 50%. This had the benefit of reducing the runoff of saline groundwater, though contributed to a growing water supply crisis.



From Kinal and Stoneman (2012): Annual streamflow in relation to annual rainfall. Note the reducing runoff (streamflow) to rainfall relationship.

Petrone *et. al.* (2010) assessed runoff on the Darling Plateau into Perth's water supply dams, finding that from 1989–2008 there was no significant trend in annual rainfall, "*however, the majority of reservoir inflow (7 of 9) and streamflow (13 of 18) records showed significant negative trends ... The rate of streamflow decline was greater in the last twenty year period than over the long-term record and ranged from −1.6 to −20.0 mm yr^{-1}*". There was also a significant negative shift in runoff following the particularly dry year in 2001.

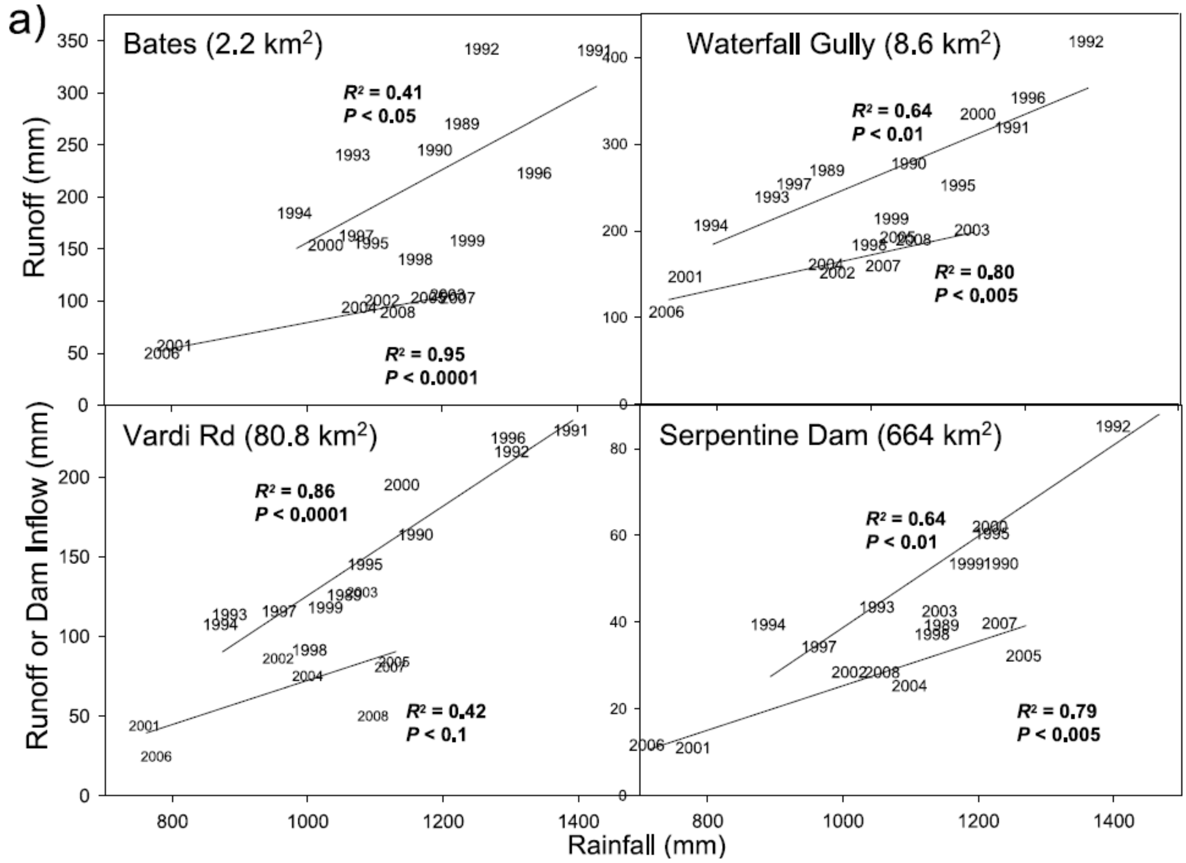


Figure 3. (a) from Petrone *et. al.* (2010): Relationship between annual rainfall and runoff for the Bates, Waterfall Gully and Vardi Rd catchments and the Serpentine dam. Regression lines represent the 1989–2000 and 2001–2008 periods. Note the significant reduction in the volume of runoff for a given rainfall since 2001.

Petrone *et. al.* (2010) hypothesise that when evapotranspiration is in excess of precipitation during a low rainfall year it would create a deficit in soil moisture storage that is carried into the following year, progressively reducing groundwater reserves over years and thus the ability to generate runoff:

> *In our study, a decline in soil moisture and groundwater levels in the last decade may be driving the decline in the proportion of rainfall that becomes runoff. Furthermore, groundwater surface water connectivity that is crucial in maintaining baseflow has likely uncoupled in several catchments that now cease to flow in the summer months. We found that perennial streams are now less common in drinking water catchments, and further stream drying may modify the assemblage of stream biota [Boulton, 2003] and influence the succession of riparian vegetation [Naiman and Decamps, 1997].*
>
> *... Shifts in flow distribution for native forest streams are likely related to falling groundwater levels and loss of groundwater-surface water connectivity, contributing to lower annual*

> *runoff. Current declines in catchment runoff and reservoir inflows have important implications for future water supply as well as the ecological function of aquatic ecosystems.*

As most of Perth's dam catchments are managed for timber production (or have been in the past), or Bauxite mining, the conversion of the forest to regrowth undoubtedly is a major contributor to the declining runoff. In their review of south-west Australian forest silviculture, Burrows *et. al.* (2011) comment on the parlous state of the remaining forests:

> *Reduced rainfall together with high water use in heavily stocked regrowth forests is resulting in little or no runoff, significantly reduced environmental water and increasing incidence of drought deaths. More than 100 years of timber harvesting has altered the forest structure such that today there is a higher density of trees in the smaller size classes over a larger area. There is some evidence that older, relatively even-aged regrowth stands use more water than the old growth forests they replaced.*
>
> *...*
>
> *Where concerns once focused on issues of salinity and Phytophthora infestation due to rising water tables, they have now shifted to the potential for ecosystem collapse, or more likely disappearance, as the water tables have disconnected from the streams, leaving riparian and aquatic communities waterless. There is a potable water need, a forest health and productivity need, and a biodiversity need to manage water balance in these forests.*

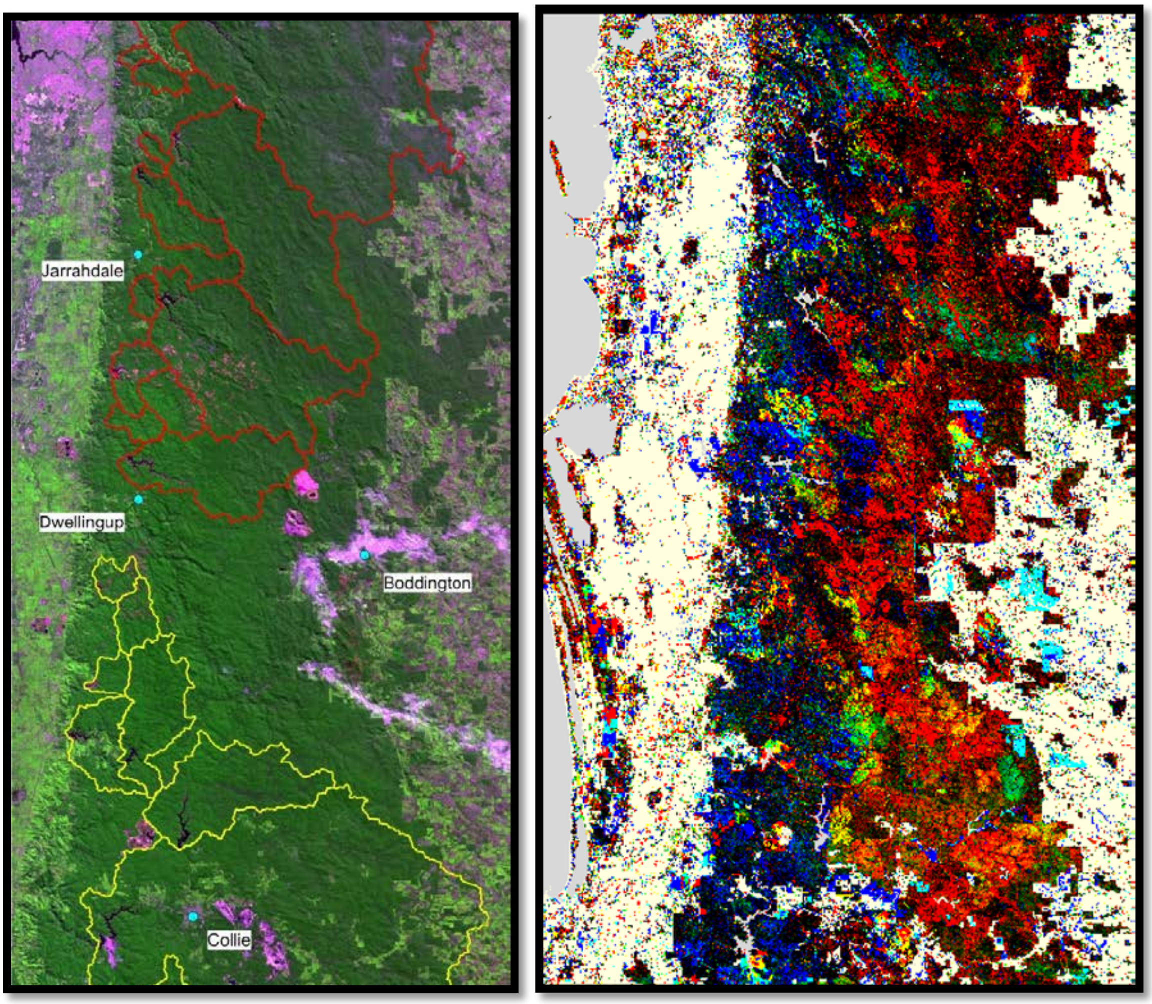
As with most of Perth's water supply catchments, the vast majority of the 664km^2 catchment of the Serpentine Dam is public land managed for logging (Department of Water 2007). It is strange, to say the least, that the management plan for the Serpentine Dam Catchment Area (Department of Water 2007) recognises that runoff into the dam has declined but makes no connection between this and the increased transpiration of the logging regrowth, instead solely focussing on water quality issues while ignoring water quantity issues. Similarly Petrone *et. al.* (2010) managed to ignore the 'elephant in the room' that is logging's effect on transpiration.

This disconnect was not apparent when it came to justifying more logging of the catchments. Amidst great fanfare, in 2005 the Western Australian Government announced its $20million Wungong Catchment Research Project which was meant to herald the delivery of 40 billion litres (gigalitres) of extra water a year to Perth's reservoirs by thinning regrowth. The 12 year 'trial' was meant to cover 7,900ha. The 'trial' was terminated in 2013 after thinning 1,800 hectares of the Wungong catchment. It found that in some years there could be an increase in runoff , though in years of poor rainfall "*particularly in years 2006, 2010 and 2012, there was no measurable increase in streamflow at the dam as a result of catchment management*" (Water Corporation, 2017). Given the failure of this 'trial' it is not surprising that the monitoring was stopped early and that no details of the outcomes were found online. It appears that the initial increase in runoff was short lived and the subsequent decline in runoff seems to have been quicker than that identified by Bari and Ruprecht (2003).

Despite the failure of the on-ground trials, and the curtailing of monitoring, the Government has pursued the idea of reducing the "Leaf Area Index" (LAI) of the forest by thinning. Modelling has been used based on Landsat images that identify surrogates (of questionable veracity) for LAI. These have confirmed the over-riding importance of vegetation structure in determining runoff.

Li *et. al.* (2010) analysed forest and catchment data from the southwest region spanning nineteen years to estimate effects of forest density on runoff and to predict changes in runoff associated with forest management and rainfall scenarios. As a surrogate measure for forest density and disturbance they relied upon a simple spectral index over a time series of Landsat TM imagery to identify vegetation changes (ForestIndex). As well as this surrogate they included topographical variables and a host of rainfall variables. They used the rainfall-runoff ratio to identify the relative significance of variables, concluding that (aside from location) 'ForestIndex' was the most significant variable to explain changes in runoff, noting:

> *... that higher vegetation cover as indicated by ForestIndex is generally negatively associated with [rainfall-runoff ratio]. This is in accord with the common understanding that more vegetation leads to higher water consumption and less water yield.*



LEFT: Figure 2 from Croton *et. al* (2013); Northern jarrah forest water-supply catchments (red and yellow outlines) within the Integrated Water Supply System (IWSS). RIGHT: Figure 5 from Li et. al. (2010): Cover trends image 1989-2007 for perennial vegetation south-east of Perth (100x160km). Red indicates linear decline in cover index; blue linear cover index increase. Green, yellow and cyan indicate curvature in the response over time. Black areas are more stable. Note the widespread forest decline (red) in the eastern part of the forest area, apparently showing ecosystem collapse and indicating a possible breakdown of the inland transport processes for atmospheric moisture.

Croton *et. al.* (2013) confirmed that "*when the present hydrology of the northern jarrah forest is assessed, it is a system where soil-water storages, groundwater levels and streamflows have declined from historical levels, and left to its own devices they are likely to decline further*". They concluded from their modelling of LAI and future climate change "*if the CSIRO Mk 3.5 climate scenario were to occur in the absence of major reductions in LAI, then all streamflow within the* *northern jarrah forest would disappear by 2070, and even by 2050 the majority of the northern jarrah forest would be producing no streamflow*"..

Croton *et. al.* (2013)'s solution is to undertake radical and frequent thinning of vast tracts of the higher rainfall areas to reduce LAI (and thereby evapotranspiration) with the hope of increasing runoff. This approach is likely to be driven by timber production objectives. Aside from their Wungong experiment proving this doesn't necessarily work, this is being proposed with no consideration of the consequences that reduced evaporative cooling, atmospheric moisture and cloud cover will have on the already tenuous hydrological cycle. They should know better by now.

It is evident that south-west Australia has an ongoing water crisis largely of their own making. Deforestation has the effect of lowering rainfall, raising watertables, and causing salinisation. Logging, and mining rehabilitation, has the effect of increasing evapotranspiration and lowering watertables. The vegetation obviously had the balance between these divergent influences 'just right', until it was irrevocably destroyed by the heavy-handed and ill-informed approach to native vegetation practiced over the past 200 years. What is most worrying is that vegetation management in Western Australia still appears to be driven by mining and logging interests, while inconvenient studies and facts are ignored. While ever this continues the Western Australian climate will continue to degrade.

While global warming is real and is contributing to Western Australia's deteriorating climate, which will increase in magnitude over time, other causes such as those relating to deforestation and vegetation degradation are being swept under the cover of CO^2 induced climate change.

The experience in south-western Australia is being repeated around Australia, with the Murray-Darling basin also in an advance state of decline. It is apparent that clearing of native vegetation, and changes to vegetation structure resulting from grazing and logging practices, are having profound impacts on rainfall and runoff around the south and east of Australia. It is urgent that we remove the blinkers, not be dictated to by vested interests, and learn from these experiences. We need to actively seek to halt and reverse the decline. The Western Australian experience is that once tipping points are reached it is not easy, and may prove impossible, to repair the damage.

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