Carbon uptake and water use of vegetation under climate change

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Key points

Human-induced climate change has been heating the earth’s atmosphere due to an accelerated accumulation of greenhouse gases (particularly CO₂) since industrialisation.

Carbon emission trading schemes are being developed by a number of countries to cap and reduce CO₂ emissions while minimising fiscal impacts.

Accumulation and storage of carbon in trees is one method of sequestration which may help offset increasing atmospheric CO₂ concentrations. However, for every molecule of CO₂ absorbed by a leaf, up to a thousand molecules of water are released as transpiration, water that has moved out of the soil into the atmosphere. Therefore, simply planting more trees to absorb more CO₂ is not as risk-free as may originally be thought, especially in the dry continent that is Australia.

The location for planting trees is also an important factor when considering their impact on water supplies. Trees use more water than grasses and shrubs and the productivity of trees is strongly influenced by water availability. Sites with more rainfall have faster rates of carbon accumulation and store more carbon. Whether trees should be planted in groundwater discharge zones or recharge zones is an important consideration when planting trees.

Water use of a stand of trees changes as it ages. The period of greatest water use coincides with the period of most rapid carbon accumulation.

Water is a scarce resource in Australia so any climate mitigation schemes involving reforestation must also consider the environmental, social and economic cost of water used by the new plantation.

Climate change

The term climate change refers to any change in climate over time, whether due to human activity or as a result of natural processes. Geological records show that as the world has become industrialised, human activities have had a much larger impact on climate fluctuations than have natural processes. Data from ice cores spanning many thousands of years indicate that global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased significantly since 1750 and now far exceed pre-industrial values. Increases in atmospheric carbon dioxide are primarily due to burning fossil fuels and land use change (particularly deforestation) while agricultural activities have stimulated the production of methane and nitrous oxide.

The impact of these greenhouse gases is to warm the near-surface global temperatures through the greenhouse effect. Greenhouse gases absorb and emit radiation and are essential for maintaining the relatively warm, inhabitable temperatures of the earth.

When concentrations of greenhouse gases increase, global temperatures increase.

Besides increases in atmospheric greenhouse gases, other climatic changes which have been recorded include warming of the climate, indicated by increasing global average air and ocean temperatures, extensive melting of snow and polar ice caps and rising of the global average sea level. Fluctuations in the amount, timing and patterns of rainfall, wind patterns, and increased frequency of extreme weather events such as droughts, heat waves and intense cyclones have also been observed.
Atmospheric concentrations of greenhouse gases can be converted to values of radiative forcing, where positive forcing causes warming while negative forcing causes cooling of the atmosphere. Global climate models are mathematical representations of the physical and biophysical processes driving the Earth’s climate. Climate models use values of radiative forcing to predict climatic changes according to various emissions scenarios. For instance, for a range of emissions scenarios, global air temperatures are expected to rise 0.2°C for each of the next two decades and even if all atmospheric concentrations of greenhouse gases had been maintained at 2000 levels, a warming of 0.1°C would be expected for each decade. Patterns of precipitation, wind and extreme weather events can also be modeled with regional-scale models to project the finer-scale implications of climate change.

Perhaps the most concerning projected change in the climate in Australia is the reduction in total annual rainfall. Australia is already the driest continent on earth. With on-going reductions in incoming water, the landscape will become progressively drier. Limited water availability will impact on the productivity of agriculture, industry and native ecosystems. There is abundant observational and projected evidence to suggest that freshwater resources are highly vulnerable to the impacts of climate change, particularly in dry environments because dry ecosystems are more responsive to changes in atmospheric CO₂, temperature and precipitation.

### Greenhouse gas concentrations before and after industrial development and their radiative forcing values.

**Atmospheric concentrations are parts per million (ppm), parts per billion (ppb) and parts per thousand (ppt).**

<table>
<thead>
<tr>
<th>Gas</th>
<th>Pre-industrial atmospheric concentration</th>
<th>Current concentrations</th>
<th>% increase</th>
<th>% of total greenhouse gas emissions (2000)</th>
<th>Radiative forcing (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>280 ppm</td>
<td>384 ppm</td>
<td>37</td>
<td>72</td>
<td>1.53</td>
</tr>
<tr>
<td>Methane</td>
<td>700 ppb</td>
<td>1745 ppb</td>
<td>149</td>
<td>18</td>
<td>0.48</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>270 ppb</td>
<td>314 ppb</td>
<td>16</td>
<td>9</td>
<td>0.15</td>
</tr>
<tr>
<td>CFC-12</td>
<td>0</td>
<td>533ppt</td>
<td>NA</td>
<td>NA</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Carbon trading

Carbon pollution reduction schemes are used to limit carbon pollution while minimising the impact on industry and domestic activities. Frameworks for reducing carbon pollution include: capping carbon pollution and trading of a limited number of permits allowing carbon pollution. Under the system proposed for Australia, the Australian Government will set a cap on the total amount of carbon pollution allowed by the sectors covered. Those industries that generate CO₂ will need to acquire a permit for every tonne of gas they emit but permits will be limited to the total annual cap for that year. At the end of the year, each company will need to surrender a permit for every tonne of carbon pollution produced during that year.

Permits will be bought and sold in the market so the price of permits will be set by demand. Companies will be able to reduce costs by reducing carbon pollution so there will be a financial incentive to reduce CO₂ emissions. During the transitional period, some companies might receive free permits but these will also have a market value so companies can choose to sell the permits or use them. The price of permits will not be set by the government. It will be determined by market forces. If a company can adapt its processes, adopt new technologies or switch to clean power more cheaply than the market price of permits, it will choose to reduce carbon pollution rather than purchase permits.

A broad range of industries will be covered from the commencement of the scheme, including stationary energy, transport, industrial processes, waste and emissions from oil and gas production. All six greenhouse gases listed in the Kyoto protocol will be included and the emphasis will be on upstream reductions in greenhouse gas emissions to reduce the number of firms requiring permits. Agricultural emissions will not be included until 2015 at the earliest because reliable methods for calculating emissions and practical enforcement strategies are not yet available. Government restrictions on land clearing have helped reduce agricultural emissions since 1990.

Under the scheme, goods and services requiring intense emissions will rise in price more steeply than less-polluting goods and services. Therefore, consumers will have a financial incentive to purchase products which are produced in less-polluting ways, encouraging investment in low emissions technologies and helping Australia to further reduce emissions. The things we produce, the way we produce them and the things we buy will be influenced by the carbon pollution reduction scheme.

A trading scheme is favoured over other approaches (such as a carbon tax) because the market mechanism of the permits encourages emitters to seek out low-cost alternatives to polluting, thereby minimising the cost to the community. Furthermore, the high cost of power will encourage consumers to conserve electricity and gas, reducing demand and emissions. Thus, the scheme will drive emissions down in several ways. A trading scheme also allows the government to directly limit the quantity of overall emissions more effectively so progressive targets of emission reduction can be met.

A trading scheme also has the potential to incorporate offsets, which are processes which allow the direct removal of greenhouse gas emissions from the atmosphere. Offsets could be allocated credits which could be used to make up the difference between a company’s total emissions and the permits held at the end of the compliance period. Examples of offsets include carbon capture and storage in forests and industrial processes that capture CO₂, (e.g. geosequestration of CO₂ deep underground). Because forests will most likely store more carbon than they produce, the forestry industry will take part in the Australian emissions reduction scheme on a voluntary basis.

Emissions trading schemes have been implemented or are being planned by a number of countries. The first schemes commenced in 2005 including 27 European countries, Norway and a voluntary scheme in Japan. In America and Canada 28 states and provinces are planning emissions trading schemes and New Zealand recently began its program. The coverage of the schemes and the emissions targets vary widely between schemes with some covering all greenhouse gas pollution while others focus only on emissions from certain industries. Some reduction targets are highly ambitious but most are conservative to begin with.
<table>
<thead>
<tr>
<th>Name of Scheme</th>
<th>Scheme inclusions</th>
<th>Year commenced</th>
<th>Countries involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Emissions Trading Scheme</td>
<td>Cap CO₂ emissions from energy and industrial sectors</td>
<td>2005</td>
<td>27 European countries and linked to non-European countries such as Norway, Iceland, Liechtenstein and Switzerland</td>
</tr>
<tr>
<td>New Zealand Emissions Trading Scheme</td>
<td>Initially covers forestry with expansion to all sectors and gases by 2013</td>
<td>2008</td>
<td>New Zealand</td>
</tr>
<tr>
<td>Norwegian Emissions Trading Scheme</td>
<td>Covers CO₂ emissions from energy, oil, coking coal and industrial production</td>
<td>2005</td>
<td>Norway, linked with EETS since October 2007</td>
</tr>
<tr>
<td>Japanese Voluntary Emissions Trading Scheme</td>
<td>Voluntary trial between 31 businesses, government is considering developing broader scheme</td>
<td>2005</td>
<td>Japan</td>
</tr>
<tr>
<td>Canadian Emissions Trading Scheme</td>
<td>Will cover half emissions from electricity, oil, gas, iron, steel, cement, chemicals and fertiliser</td>
<td>2010</td>
<td>Canada</td>
</tr>
<tr>
<td>Regional Greenhouse Gas Initiative</td>
<td>Constrain emissions from power plants to 2009 levels then reduce by 10% by 2019</td>
<td>January 2009</td>
<td>North east and Mid-Atlantic states of USA</td>
</tr>
<tr>
<td>Western Climate Initiative</td>
<td>Reduction of aggregate emissions to 15% below 2005 levels by 2020</td>
<td>Not specified</td>
<td>USA states of Arizona, California, New Mexico, Oregon, Washington, Utah, Montana and Canadian provinces of British Columbia and Manitoba</td>
</tr>
<tr>
<td>Midwestern Greenhouse Gas Accord</td>
<td>Design of scheme yet to be finalised</td>
<td>November 2008</td>
<td>USA states of Minnesota, Wisconsin, Illinois, Iowa, Michigan and Kansas and Canadian Province of Manitoba</td>
</tr>
</tbody>
</table>

**The potential for carbon sequestration by planting trees**

Forests play an integral role in the global carbon cycle. Trees are carbon stores, so limiting loss of native vegetation and planting new forests will help reduce net greenhouse gas emissions in Australia. Photosynthesis converts light energy into chemical energy, creating oxygen and carbohydrates from CO₂ and water. The process of carbon fixation whereby CO₂ is changed into organic materials provides energy for the plant to survive, grow and reproduce. The accumulation of biomass in stems and roots locks the carbon away for very many years, so forests and plantations become carbon sinks as they expand and grow. Carbon can also be stored in the soils of mature forests. Regular cultivation and heavy grazing can deplete soil carbon stores so reforestation of land can be particularly effective.

The world’s forests and soils store more than one trillion tonnes of C, more than twice as much as the atmosphere.
The reforestation of land previously used for other purposes has the potential to significantly increase the storage of carbon from the atmosphere. When trees are felled, the amount of carbon which is returned to the atmosphere varies, depending on the use of the wood and the subsequent use of the land. Carbon is also released back into the atmosphere following bushfire through burning and decay. While a forest is actively growing and sequestering carbon, it is termed a carbon sink.

Carbon stores can be separated into above-ground and below-ground components. Above-ground sequestration of carbon principally involves storage of carbon in stems and large branches as these are long-lived. Storage in leaves is generally an unimportant consideration because of their short life, relative to stems. Below-ground stores include carbon stored in roots and soil carbon, also known as soil organic matter (SOM). Carbon enters the soil through active roots and the decomposition of plant and animal matter. SOM can be a source or a sink of atmospheric carbon depending on the land-use type, climatic conditions and management practices.

Generally, the more dense the vegetation, the higher the concentration of SOM and increasing the use of mulch, compost and manure will increase SOM. Actively growing roots are associated with essential soil microbes which aid in the accumulation of SOM. Healthy forests provide perfect conditions for microbial activity and the long-term accumulation of carbon in the SOM. Active soil microbes promote availability of soil minerals and nutrients for plants, improve soil structure, increase water retention and increase respiration. Thus building soil carbon stores improves soil health and many land managers are taking steps to improve soil productivity.

There are several commercial products which are being developed as catalysts for the accumulation of SOM. Land clearing, erosion and drought can all lead to losses in SOM.

Despite the benefits of forest establishment to SOM, there are several circumstances which should be considered when calculating changes in SOM under changed land use conditions. For instance, decreases in SOM occur when pine plantations are established on improved pastoral land in temperate regions, but increases in SOM will be maximised when broadleaf plantations or nitrogen-fixing species are established on previously cropped land in tropical and subtropical regions. Thus, the previous land use, climate and type of plantation must all be considered to maximise SOM. Accumulation of SOM is also maximised by longer forest rotations (20-50 years). This is because soil carbon in the top 10 cm generally decreases by about 3.5% per year for the first five years of forest establishment and while this rate of decrease gradually declines and eventually recovers, soil carbon does not equilibrate with soil carbon in agricultural soils until the forest is about 30 years old.

When SOM is considered together with litter, however, the establishment of forests generally increases C accumulation within the ecosystem because of larger leaf volume and litter pools in forests compared to pastures and crops.

As trees in a plantation establish themselves, productivity (defined as g C fixed /ha/year) gradually increases. Carbon sequestration rates generally peak when a plantation is around 10 to 20 years old (depending on how fast the species grows). Beyond that time, the rate of accumulation of biomass slows down. If trees are not harvested, the forest will continue to accumulate carbon at a gradually decreasing rate until growth is balanced by decay at maturity (around 100-200 years). At this point, the forest is C neutral because the rate of accumulation and loss of C are balanced.

The rate at which forests accumulate carbon depends on the climate, topography, soils, tree characteristics and management practices. Management decisions such as the number of trees planted per hectare, quality of site preparation, seedling survival and protection from fire and pests can maximise C accumulation.

As well as helping to limit greenhouse gas emissions, conservation of forests can aid in prevention of land degradation and salinity while maintaining water quality and biodiversity.

The proposed carbon pollution reduction scheme for Australia will encourage reforestation by allocating permits to forest owners for the net sequestration of carbon as forests grow. Forests in Australia store approximately 10.5 billion tonnes of C within the plant material
(excluding soil C) and this is distributed at approximately 4 tonnes of C per ha across Australia. This store represents the removal of 38.5 billion tonnes of CO₂ from the atmosphere, since about half the dry weight of a tree is C and one tonne of C represents 3.67 tonnes of CO₂. Carbon stored in wood is only released back into the atmosphere through decay and burning. Using wood in long-lived houses and furniture is preferable to using wood in the production of paper because of the long life of the former and the short life of the latter. Forests planted on agricultural land can remove 5-30 tonnes of CO₂ per ha from the atmosphere each year.

As atmospheric concentrations of CO₂ increase, productivity of trees can be enhanced through greater availability of CO₂. This will allow trees to grow faster but most recent studies are suggesting trees may not actually become larger at maturity. Accumulation of carbon in landscapes with trees may become more rapid as the atmosphere is further enriched with CO₂ but results from recent experiments show highly variable results. Differential responses to CO₂ enrichment are associated with water availability at the site as discussed below.

Water and carbon relations of forests

The value of forests as sinks for carbon storage must be considered in conjunction with the costs of creating and maintaining those carbon stores. Specifically, water use in forests may limit their potential as carbon offsets, particularly on a dry continent like Australia where water is in limited supply.

Transpiration in trees occurs through the stomatal pores in leaves. Stomata open to allow CO₂ into the plant for photosynthesis but at the same time, water vapour escapes to the atmosphere. Closing stomata or limiting opening will retain water within the plant but it also generally limits photosynthesis and hence C uptake.

Compared with pasture or grasslands, a mature forest uses far more water per unit land area per year. That is, evapotranspiration is higher from forests than pasture or grasslands on an annual basis. Evapotranspiration of trees is much higher than grasses for three reasons. Trees have deeper roots, larger root biomass and surface area which allows them to access more soil water. Forests have a larger leaf area index. This provides more pores for water to escape from leaves and also increases interception losses (the water that is captured on a canopy and then evaporated to the atmosphere). Trees use water all year whilst pastures and crops generally use water for only a fraction of a year. Together, these increases in transpiration and evaporation cause increased evapotranspiration. As evapotranspiration increases, the remaining rainfall available for other uses (known as the water yield) decreases according to the following equation:

$$Q = P - ET,$$

where Q is water yield (consisting of surface run-off, groundwater recharge and lateral flow to streams), P is precipitation and ET is evapotranspiration (consisting of transpiration from vegetation, interception losses from the canopy after rain and evaporation from soil).

Changes in forest cover and condition (such as the age of the forest, state of recovery after a disturbance etc.) affect the water yield of a catchment. Generally, an increase in the area of land covered by forest in a catchment decreases the water yield of that catchment and changes in yield are approximately proportional to changes in forested area. Similarly, as annual rainfall increases annual tree water use increases but runoff also increases as there is more water available.

A simplified diagram of the carbon cycle. Arrows represent fluxes between various sinks and sources. Numbers represent the amount of carbon across the globe stored in each sink in Giga tonnes ($10^9$ tonnes) of carbon.
As a forest matures, its water requirements change, as does its productivity. These changes are associated with changes in stand density, which affects leaf area, sapwood area and interception losses. For example, in a Mountain Ash forest north of Melbourne, it has been shown that during the first 25 years of vegetation regrowth after disturbance (such as a fire), average annual water yield declines. Beyond 25 years, the water yield gradually increases and stabilises at about 150 years maturity (see graphs below).

Runoff from a catchment increases as rainfall increases (from Zhang et al. 1999).


This idealised curve (known as the Kuczera curve) is a hypothetical composite of data derived from contrasting catchments. There is substantial error associated with the estimates of water yield throughout the timeline. However, measurements of changes in stand structure as a forest matures outlined below support the functional form of the Kuczera curve. These data are based on a series of studies investigating the water balance of a Mountain Ash forest within the watersupply catchment for Melbourne. Measurements were made after an intense fire destroyed most of the forest so the age of stands was accurately determined.

When the Mountain Ash canopy is destroyed by fire, seeds are released from woody capsules and a dense regrowth of seedlings germinates. The density of tree stems declines after establishment through a self-thinning process as shaded individuals are unable to acquire sufficient light. Stand water use is driven more by leaf area and sapwood area than stem density, so the changes in the amount of foliage and conducting tissue in the stems must be considered to understand how water yield changes with stand age.

The leaf area index (LAI, calculated as the area of leaves per area of ground) increases in a very young stand as saplings shoot up and increase their leaf area. After about 20 years of growth, the total foliage per unit ground area begins to decline. LAI and stand water use are positively correlated, so the associated effects on stand water use are an initial increase as LAI increases and then a decrease with decreasing LAI.

Sapwood area also varies with the age of the forest, whereby sapwood area declines as the forest matures. Because the velocity of sap remains constant with forest age, the declining surface area of conductive tissue through which water moves causes water use to decline with stand age.

Changes in canopy interception losses as a stand ages. Redrawn from Vertessy et al. 1998.

The overall result of changing LAI, sapwood area and interception losses is that water yield increases as the forest matures beyond 60 years. As a proportion of rainfall, transpiration of trees decreases while transpiration of the understory increases. Together, total evapotranspiration decreases once the forest reaches 60 years of age, leaving more water as runoff. This is consistent with the Kuczera curve.

As a Mountain Ash forest matures, the sapwood area per ha of forest declines. Source: Vertessy et al. 1998.

Finally, canopy interception increases sharply for the first 20-30 years of forest regeneration, then reaches a limit and declines slightly. Canopy interception involves the capture of rainfall by vegetation and litter. This water is subsequently evaporated to the atmosphere as interception losses and is therefore an unproductive loss of water from the catchment. Interception losses vary with ecosystem age and type due to differences in leaf area and branch angle. Rainfall characteristics also have an effect, as many short, light intensity rainfall events will have more interception losses than long duration heavy rainfall events.

The proportion of run-off, tree transpiration, understory transpiration and soil evaporation changes as a stand of mountain ash ages. Data from Vertessy et al. 1998.

Just as rainfall influences tree water use, rainfall also affects primary productivity of trees. Net primary productivity (NPP) is gross photosynthesis minus respiration and it represents the maximum potential accumulation of carbon in an ecosystem. As rainfall increases, NPP also increases on a continental scale so the continent with the largest rainfall (South America) also has the largest NPP.
Estimates of total continental net primary productivity (NPP), NPP per land area and water use efficiency (total NPP/rainfall). Data from Eamus (2003), Europe was removed because it has very little natural vegetation remaining.

<table>
<thead>
<tr>
<th>Continent</th>
<th>NPP of natural vegetation [Gt C year⁻¹]</th>
<th>Land area [km² x 10⁶]</th>
<th>NPP/land area [t C yr⁻¹ km⁻²]</th>
<th>Mean annual rainfall [mm]</th>
<th>NPP/rainfall [t C km⁻² mm⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>12</td>
<td>30.3</td>
<td>396</td>
<td>720</td>
<td>0.55</td>
</tr>
<tr>
<td>North America</td>
<td>6</td>
<td>9.5</td>
<td>630</td>
<td>800</td>
<td>0.79</td>
</tr>
<tr>
<td>South America</td>
<td>14</td>
<td>17.8</td>
<td>787</td>
<td>1800</td>
<td>0.44</td>
</tr>
<tr>
<td>Asia</td>
<td>12</td>
<td>44.8</td>
<td>268</td>
<td>620</td>
<td>0.43</td>
</tr>
<tr>
<td>Australia</td>
<td>2</td>
<td>7.7</td>
<td>260</td>
<td>480</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Within a continent, total tree carbon stored and tree carbon accumulated increases at sites with larger rainfall. The following figures show data for a theoretical plantation established at three sites with varying rainfall across Australia. The mean annual rainfalls for Cairns, Albany and Griffith are approximately 2000, 900 and 400 mm respectively. This reduction in rainfall causes a reduction in the amount of carbon stored in trees and a reduction in the rate at which carbon is accumulated.

The reasons for increased productivity under wetter conditions are that an enhanced supply of water reduces the role of water in limiting productivity. More rain leads to more moist soils which allow a plant to support a larger leaf area. Nutrient uptake is stimulated by moister soils as decomposition processes are stimulated and more water with higher nutrient concentrations is absorbed by the plant. Greater leaf area, more water and nutrients all act together to stimulate photosynthesis. Consequently, the greatest potential for carbon accumulation and storage occurs at sites with high rainfall. Conversely, where rain is scarce, water limitation prevents plants from photosynthesising at peak levels, thereby reducing productivity.
Since for most locations in Australia productivity is water-limited, the potential for carbon sequestration is limited by water availability. Furthermore, accumulation of carbon is most rapid when a stand is around 10 to 30 years of age. However, this is also the period when stand water use is greatest.

As CO₂ concentrations in the atmosphere continue to increase, the water-use-efficiency (calculated as unit productivity per unit water used) of plants in water-limited conditions is likely to increase. This is because leaves can acquire sufficient CO₂ for photosynthesis with reduced stomatal opening, thereby reducing water loss from the plant. This may allow plants to be more productive while using less water but does not remove the existence of the trade-off between carbon sequestration and water use. Indeed it is likely that the increased concentration of atmospheric CO₂ that has occurred in the past 100 years may be causing woody thickening and reduced water yields in arid and semi-arid parts of Australia and globally.

Another complicating factor is the role of water and nitrogen limitation. When the availability of water limits the productivity of an ecosystem, enrichment of atmospheric CO₂ concentration causes an increase in productivity because the plant is able to use water resources more efficiently. When nitrogen is the limiting resource, however, the increase in productivity under elevated CO₂ is not as substantial as it is when water is limiting. Recent models show that productivity is maximised when a plant finds an optimum leaf nitrogen concentration, stomatal conductance and LAI. Water limitation causes a plant to make a trade-off between LAI and stomatal conductance, while nitrogen limitation causes a plant to trade-off between leaf nitrogen concentration and LAI. Under elevated CO₂, LAI is increased due to reduced stomatal conductance and foliar nitrogen concentration. This is because photosynthesis is more sensitive to CO₂ concentrations at lower stomatal conductance but less sensitive to CO₂ at lower leaf nitrogen concentrations. Thus, growth responds more to elevated CO₂ in dry years when nitrogen is plentiful than during wet years with limited nitrogen cycling.

The fact remains that to maximise carbon storage in plantations and forests, water resources must be managed very carefully.

**A review of the international and Australian literature on water yields and reforestation and deforestation**

Trees use more water than shrubs, grasses and unirrigated crops and pastures. A recent global review of the literature found that annual run-off declined by 44% and 31% when grasslands and shrublands were converted to forests, respectively. There is some variation between catchments due to differences in the seasonal patterns of rainfall and water use and differences between the location of plantations in the landscape, catchment soil types and topography. However, the main difference between catchments is due to whether it is covered predominantly by trees or grasses.

![Annual water use for forests and pastures increases with rainfall and forests have larger water needs than pastures. Redrawn from Zhang et al. (2003).](image)

As a result of greater water use by trees, less water leaves a forest and the water yield of a forested catchment is smaller than that of a grassed catchment. A smaller water yield means less water for stream flow, irrigation, and other human uses.

The most important factors controlling annual water yield of a catchment are rainfall and the type of vegetation cover. If the annual water yield is the difference between the rainfall and the water used by vegetation, we can plot the change in water yield at different rainfalls if a pasture was changed to a forest. This demonstrates that the amount of extra water used by forests ranges from about 10% of rainfall at sites receiving 1000 mm to about 20% at sites receiving 2500 mm of rain.
Change in water yield when a catchment is converted from pasture to forest.

It is rare for an entire catchment to be converted from pasture to forest but the impact of vegetation change on catchment water balance is significant even for small areas of afforestation. For instance, consider a small catchment of 10 km², which has a change in vegetation cover causing a 10 mm increase in water use. We know that one mm per year is equivalent to one megalitre (ML) per km² of catchment so that 10 mm change in water use causes a 100 ML deficit in water yield across the catchment. That is equivalent to 100 Olympic-sized swimming pools of water being lost to the atmosphere each year. Similarly, for each hectare of trees planted in an 800 mm rainfall zone, the water yield decreases by approximately 1.5 ML.

The most productive areas for forests will be those with the largest rainfall so they will also be the most impacted by changes in vegetation cover. Within the Murray Darling Basin, land having annual rainfall of above 800 mm is the most suitable for wood production. Within these areas, complete conversion to plantations would result in water yield reductions of between 25 and 450 mm. Estimates of the impact of doubling of plantation area across the entire catchment by 2020 indicate that water yield will decrease between 550 and 700 GL per year, depending on where the trees are planted. This will result in significant change in streamflow, threatening water security and environmental flows. The seasonality of these changes must also be considered so sufficient water remains during very dry periods.

During dry periods, trees can maintain relatively high water use by accessing deep soil water stores. As a result, reforestation of a catchment can significantly reduce dry season flow or even cause a stream to dry up completely. Flow duration curves show the relationship between streamflow and the percentage time that particular flow is exceeded. They can be used to show different time scales, compare catchments and compare vegetation covers. An annual flow duration curve provides a cumulative representation of the number of days when the daily flow exceeds a certain value.

The vegetation comparison in the next figure shows that in this example catchment, the daily flow exceeds 0.01 mm for 80% of the year under pasture but this value drops to less than 40% if the catchment is covered by a pine plantation. During periods of high flow, the two curves are much closer but at low flows, there is a larger difference between the forest and grass. Even though low flows are reduced more than high flows, the small relative reduction in higher flows accounts for the majority of the reduction in annual water yield.

There is a minimum threshold of plantation change within a catchment which needs to be met before changes in catchment water balance can be detected. This is because the change in runoff and streamflow due to reforestation depends on soil type, topography, position of a plantation in the landscape and the annual distribution of rainfall within the catchment, all of which are spatially variable. Generally at least 15–20% of smaller catchments needs to be reforested before a reduction in runoff is detectable but this proportion may be smaller in larger catchments.

Within larger catchments, the location of plantations will change the impact of the plantation on the local water balance. For example trees planted in the lower catchment will intercept more water moving as throughflow...
than those higher in the catchment. Similarly, trees planted in recharge zones can significantly reduce groundwater recharge whilst a plantation on a discharge zone will not. Forests can be planted such that they minimise water use by planting in strips across the contours of the landscape rather than in blocks perpendicular to the contours. Such an arrangement will locate trees further from streams and help maintain streamflow as outlined below.

Across much of Australia, surface and groundwater are linked so forests may impact on groundwater recharge rates. Because trees use more water than grasses and have deeper roots, forests can lower the water table. Consequently, a smaller proportion of rainfall may become groundwater recharge rather than surface flow or runoff.

Any reduction in groundwater recharge may impact on streamflow by decreasing the volume of water available to feed a stream’s baseflow in dry conditions. When there are long periods between rainfall, the reduction in baseflow can be particularly problematic. In many parts of inland Australia where there is very little surface water, groundwater is used for agriculture and other purposes. Expansion of forest in some areas such as the lower south east South Australia and around Perth in WA have had a measurable impact on groundwater levels, reducing water availability for irrigation. In such areas, forests must be included in water-use plans. The impact on groundwater will be associated with the size of the plantation and the depth of the water table.

The type of forest will also impact on the water yield. Comparisons of native eucalypt forests and Radiata pine plantations have shown that when trees are older or suffering dry conditions, pines use more water than eucalypts but when rainfall is more plentiful or the trees are young, native forests use more water. This is reflective of the ability of native forests to use water in a conservative manner under limiting conditions but maximise water use (and hence C gain) when it is abundant. However, the difference in water use between native and Radiata forests was not as great as the difference between grass and plantation.

When the proportion of annual run-off to rainfall for a site is less than 10%, vegetating that area with trees will often result in a complete loss of run-off. Furthermore, run-off will be halved when trees are planted on an area where 30% of rainfall becomes run-off in an average year.

Modelling studies in South America confirm changes in the hydrological cycle in Australia due to vegetation cover. Deciduous forests had larger evapotranspiration but smaller total discharge, groundwater recharge, and surface run-off than crops or pastures.

Conclusions
Trees accumulate carbon and therefore forests have potential as a climate mitigation tool. However, forests use far more water than shrubs and grasses so the environmental cost of reduced water yield arising from increased plantation area must be considered together with the benefits of carbon sequestration. Carbon sequestration programs must address the possibility that planting forests could intensify water shortages in many areas, particularly when water is already in limited supply.

Strategies to limit impacts of reduced water yields due to establishment of forests include planting trees at different times to create a mosaic of age-classes, locating plantations in lower rainfall areas to reduce the decline in water yield and spreading trees across many catchments to minimise the impacts on any one water course.

Despite CO₂ enrichment and climate change causing increased water use efficiency, the increased water use and reduced water yield of forests compared to grasslands is unlikely to be offset on the continental scale.
References and further reading


