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The increasing density of shrubs and trees across a landscape

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Key points

Woody thickening is a global phenomenon whereby the density of trees and woody shrubs is increasing in the landscape. Although most commonly seen in arid and semi-arid landscapes, it also occurs in other environments. This process has a number of impacts on landscape function.

Woody thickening can be a naturally occurring phenomenon but is being enhanced by climate change, changes in fire regimes and other human land use activity.

Woody thickening influences carbon storage and carbon accounting by increasing the biomass present in a landscape.

Water balances are impacted through increases in evapotranspiration, which leaves less water available for stream flow. Nitrogen cycling is also affected. Furthermore, reduced grass growth results in less food production for livestock.

Woody thickening may play a role in ameliorating salinisation of soil and groundwater by preventing rises in water tables.

An aerial view of open woodland, Richmond, NSW.

Definition and where it occurs

Woody thickening, also known as vegetation thickening, woody weed increase and woody re-growth, is the increase in woody vegetation standing biomass in a landscape already containing woody biomass. This differentiates it from woody encroachment, (also called woody plant invasion) defined as the movement of woody species into a landscape that *presently* does not contain woody species (either through management of the landscape or through other factors). For the purposes of this report, we include discussion on woody thickening and woody plant invasion and use the term woody thickening to include both phenomena.

The inverse of woody thickening is woody thinning and both processes are happening concurrently. Woody thinning is the removal of woody trees and shrubs through such processes as land clearing for agricultural purposes, increased fire frequency and degradation of soil or soil water content. Woody thickening has predominated over woody thinning in recent decades, as evidenced by the fact that there has been a residual terrestrial uptake of carbon of about 2.3 Gt per year in the global carbon balance from 1980 to 1998.

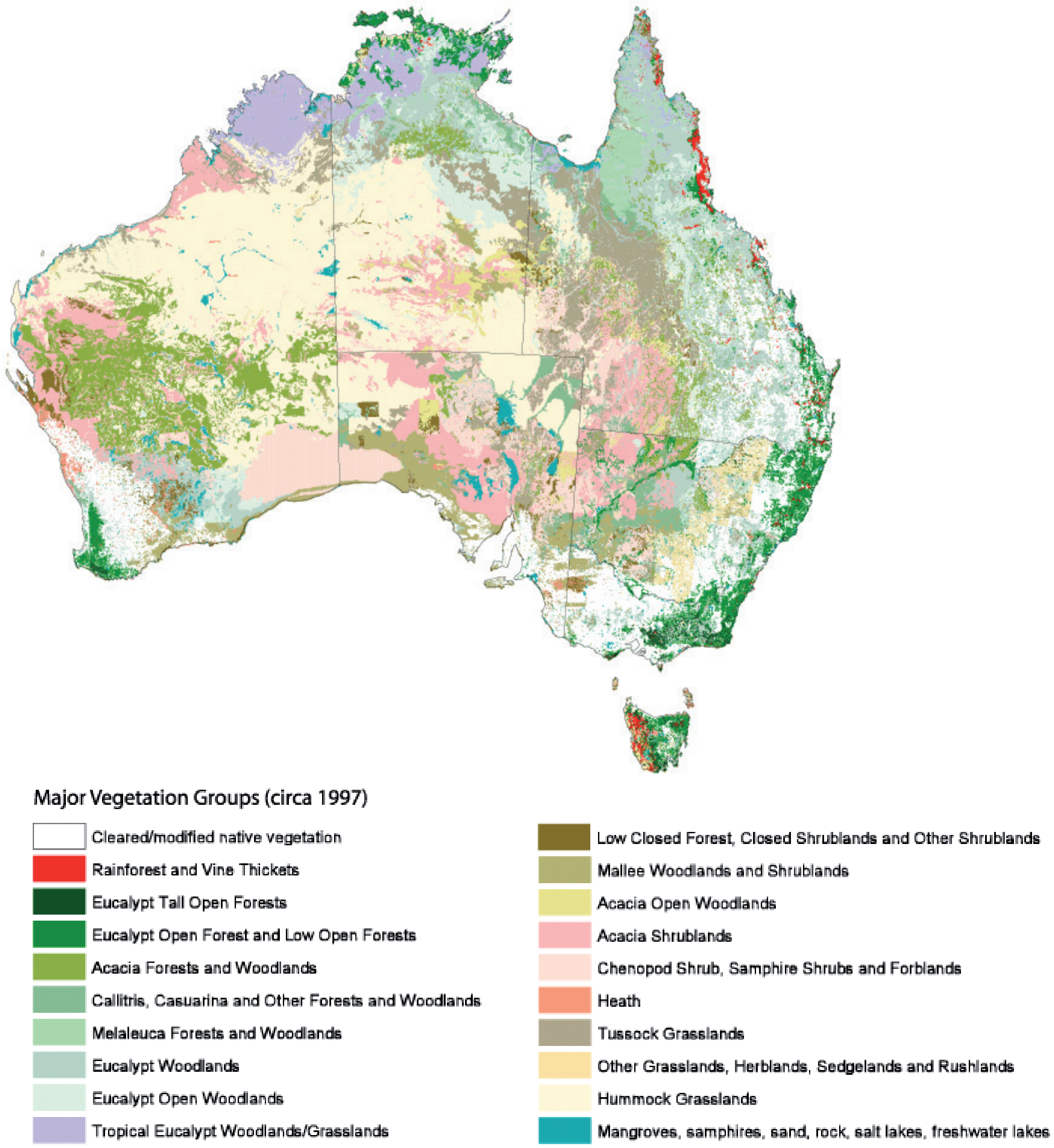
Both woody thickening and woody plant invasion are global issues that are commonly observed in arid and semi-arid regions but they are also observed in tropical rainforests of Central and South America, temperate forests globally and even isolated wetland and marsh areas.

Arid and semi-arid ecosystems cover approximately 45% of the global land surface and we concentrate on these conditions for this discussion since the majority of woody thickening globally and in Australia occurs in these regions. Australian arid and semi-arid ecosystems are made up of a mix of herbaceous and woody vegetation comprising grasses and trees or shrubs. The mix or balance of these vegetation growth forms depends on interactions between climatic variables (such as amount of precipitation and seasonality of rains), soil factors (such as texture, depth, fertility and run-off) and disturbance regimes (such as fire regime, grazing by livestock and browsing by native animals). In the last century, the balance has shifted to favour trees and shrubs over grasses in many dryland areas. The factors causing this shift (ie. woody thickening) are subject to debate and include alterations in fire frequency, grazing intensity, atmospheric CO_2 concentration and nitrogen deposition. These are discussed on subsequent pages.

The disturbance/recovery cycle where the majority of time is spent in the recovery process. Disturbance events include fire, flood, drought and human interventions such as vegetation removal or herbicide application.

Woody thickening has occurred in savannas of Africa, North and South America, south-east Asia and Australia. Savanna ecosystems are characterised by a dynamic equilibrium between competing tree and grass species but where woody thickening has occurred, the equilibrium is shifting and trees are becoming favoured. In Australia, woody thickening has occurred predominantly in savanna areas. Savannas cover 11% of the world's vegetated land, whilst savannas and open woodlands cover more than half of Australia.

Methods for documenting woody thickening include historical observations through photographs, written records or verbal history, long-term monitoring, aerial photography and satellite imagery, carbon isotope analysis, dendochronology (dating using tree rings) and use of predictive models to simulate processes of woody thickening. In extreme cases, woody thickening can have a vast impact on the landscape. For instance, in the rangelands of Northern Texas, where vegetation was left unmanaged, woody cover increased by up to 500% over 63 years.



Major vegetation groups in Australia, 1997. Woody thickening has predominantly occurred in woodlands and open forests of arid and semi-arid Australia. Map source: National Vegetation Information System, Department of the Environment, Water, Herritage and the Arts, http://www.environment.gov.au/erin/nvis/index.html

Reasons for interest in woody thickening

Carbon storage and carbon accounting

Woody thickening is an important part of the global carbon cycle because shrub and forest expansion represent a substantial component of the terrestrial carbon sink. If woody thickening were to continue unabated, the conversion of grasslands to closed woodlands would represent a terrestrial sink of 94.3 Pg of carbon. Changing dominance of vegetation to a more woody structure alters primary production, rooting depth, plant allocation and soil faunal communities, thereby influencing nutrient storage and carbon cycling. When woody thickening occurs, the amount of carbon stored in the ecosystem is generally assumed to increase. In Australia, woody thickening is thought to make a small but significant contribution to the global terrestrial carbon sink. For instance, eucalypt savanna woodlands in Queensland contribute 18 Mt of increased storage of carbon per year and another estimate of woody thickening in grazed woodlands of eastern Queensland over a 60 Mha area suggested above-ground sequestration was 28 Mt of carbon per year. This is because where grasses are replaced by trees the above-ground biomass increases considerably. The amount of increase depends on the age, productivity and density of the stand.

Considering above-ground biomass alone, carbon stock is a function of net flux and longevity (residence time) of carbon. Consequently carbon stores at a site may change due to changes in flux and/or longevity of the carbon at that site. There are three possible scenarios involving different variations in flux and longevity.

1. The first is where the new net carbon increment (NNCI, a measure of the flux) remains constant but the longevity increases because a greater proportion of carbon is accumulating in long-lived woody plants and less NNCI is contributing to short-lived plants on which stock graze.
2. The second scenario involves a decline in NNCI in conjunction with an increase in longevity in woody plants which implies a shift to schlerophyllous foliage and associated increase in the carbon to nitrogen ratio of vegetation. This often occurs when land is degraded and nutrients have been lost from the soil.
3. The third scenario occurs when NNCI increases and longevity remains constant. This leads to more foliage and woody material being present, probably associated with an increase in availability of resources for plant growth.

It is difficult to separate the effects of these three scenarios and they may all happen on grazed lands. The net effect is that there is an increase in carbon stock in living vegetation but this does not necessarily mean that woody thickening in Australia is a carbon sink as the below-ground dynamics must also be considered. Presently, soil carbon dynamics have not been properly described on a continental scale.

Below-ground, the depth and rate of turnover of roots and ease of decomposition of all plant material can either increase or decrease with woody thickening. Changes in soil organic carbon are difficult to measure and predict and may either enhance or offset above-ground biomass gains, complicating the quantification of carbon storage in newly woody sites. There is no clear relationship between changes in soil carbon stores and woody thickening, as this can be altered by site-specific variables such as precipitation and the interactions between above- and below-ground biomass. As woody vegetation density increases, there are gains in soil organic carbon at drier sites while wetter sites lose soil organic carbon. Changing rainfall regimes as a result of climate change make predictions even more difficult. Furthermore annual precipitation may not be indicative of what might happen at a particular site because total carbon assimilation into vegetation at a site depends on rainfall during the growing season rather than simply the total annual rainfall received. Consequently the intermittency and magnitude of rainfall events must be known to fully understand future variation in soil organic carbon arising from woody thickening. Finally, changes in total below-ground carbon content can occur in the opposite direction to changes in above-ground biomass. Thus, below-ground changes in response to woody thickening must be carefully considered when assessing net emissions of CO_2. Increased woody thickening may also be associated with nutrient depletion of the soil and increased soil acidity.

Fluctuations in rates of carbon cycling are often associated with precipitation events. During summer monsoonal periods in northern Australia or following summer rains in southern Australia woodlands exhibit large rates of loss of soil carbon through respiration of the soil microbial community. Access to deeper soil water by woody vegetation (described next) allows trees to increase net CO_2 gain during dry periods in comparison to grasses, which suffer severe water deficits and therefore have reduced productivity when rainfall is scarce. This is why grass cover is lost first during the early stages of seasonal dry periods or drought. Enhanced plant growth increases accumulation of leaf litter on the soil surface which may lead to higher microbial respiration rates during rainy periods that offset elevated photosynthetic CO_2 gains during dry periods. Thus greater plant density and productivity in an area vegetated by woody plants may be offset by a larger respiration response.

From this discussion about carbon accounting and carbon stocks, it is clear that the process of woody thickening poses some challenges for carbon accounting and the development of carbon inventories. In particular, problems with quantification and attribution in below-ground processes must be overcome.

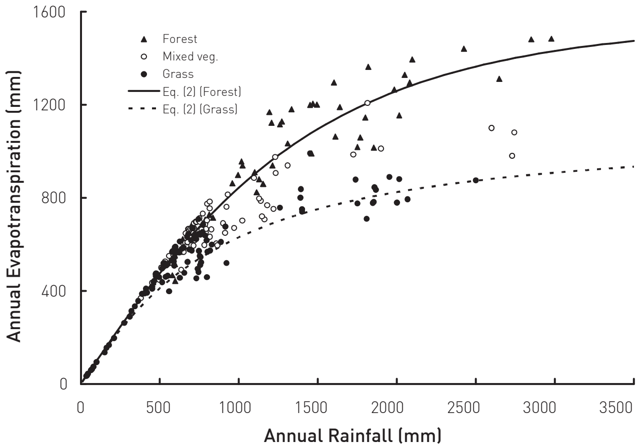
Furthermore, complex interactions between processes determining woodland dynamics must be better described and the factors which enhance woody thickening must be better understood.

Water balance of landscapes

Water cycling is fundamentally altered by vegetation change. Replacement of shortrooted grasslands or crops, which tend to use water seasonally, with deeper rooted forests that tend to use water all year, has dramatic impacts on catchment water yield (the amount of water lost from a catchment as groundwater recharge and lateral flow to rivers).

> Water yield is altered through changes in transpiration, interception and evaporation, all three of which tend to increase with woody thickening.

Transpiration rates are principally influenced by changes in rooting depth, leaf area, stomatal behaviour, plant surface albedo (the reflectance of the canopy) and turbulence (the pattern of wind over a canopy). Generally, woody thickening leads to deeper rooting depth and larger root biomass, allowing plants to access a larger volume of soil water for longer periods. Woody vegetation often uses deep soil water whereas grasses have much shallower roots and are more reliant on rainwater inputs to the upper soil. Use of deep soil water has been shown to increase with the amount of woody plant cover and the proportional use of deep water stores increases during dry periods when rainwater input is minimal. Access to larger water stores may allow increased canopy conductance (the ease with which water can move out of the canopy into the atmosphere) in woody vegetation, particularly when combined with larger leaf areas and this results in elevated transpiration compared to that of grassland.



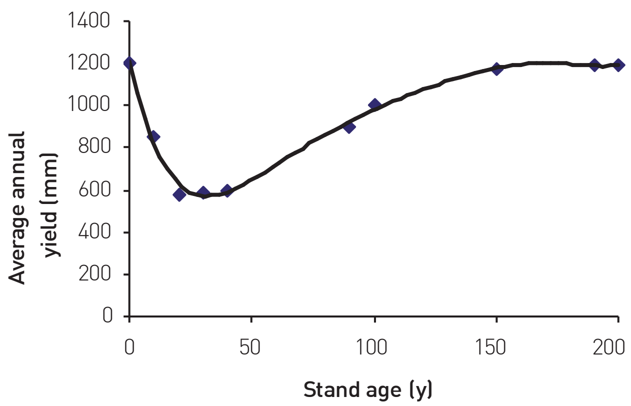
Relationship between annual evapotranspiration and rainfall for different vegetation types. After Zhang *et al*. (1999).

Transpiration is the main component driving variations in water yield associated with woody thickening but evaporation of intercepted rainfall can also be a significant factor. This can account for 10–20% in broad-leaved forests and up to 20–40% in conifers although for grassland, interception tends to be a negligible pathway for water loss. Thus, evapotranspiration (the sum of evaporation and transpiration) increases as woody thickening occurs and can be up to 40–250 mm larger in a Eucalypt plantation compared to adjacent grassland.

The net result of increasing evapotranspiration is that runoff (and therefore stream flow) decreases substantially, particularly in evergreen species. For instance, runoff in Eucalypt forests may decreased by up to 75% and decrease by up to 40% in pine plantations, in comparison to runoff for grassland. As a forest stand ages after a disturbance event such as a fire, woody thickening increases as the forest grows, causing increased evapotranspiration and declining water yield.

> In parts of Australia reduction in runoff may aid mitigation of salinisation of soils and waterways and groundwater upwelling. For example stream salinity declined from 497 μS cm^{-1} 1–4 years after reforestation to 79 μS cm^{-1} 11–15 years after reforestation in Pine Creek catchment, Vic. (van Dijk *et al*. 2007).

Where water shortages are a problem, however, woody thickening may intensify water issues and this should be considered in carbon capture and storage programs.



An idealised relationship between stand age and mean annual catchment run-off from Mountain Ash forest north of Melbourne. Redrawn from Kuczera 1985, cited in Vertessy *et al*. 1998.

It is particularly important to consider changes in runoff during times of low-flow in arid and semi-arid areas as these are the circumstances under which the most severe effects of limited water availability will be seen. Furthermore, specific details of a catchment must be considered to determine the influence of vegetation type on runoff changes. In a medium rainfall site (600–1000 mm per year), runoff from agricultural land was found to be no different from runoff from forested land (van Dijk *et al*., 2007). The same study found that expansion of a plantation may not alter runoff in large catchments but it may need to be considered in catchments less than 2000 km^2. This anomaly may be due to scale differences. Most studies assessing the effect of vegetation regime on streamflow are typically undertaken at the scale of about 50 ha and these show that evapotranspiration increases with woody thickening. Such small areas are generally composed of steeper terrain with thinner soils allowing rapid infiltration. In comparison, larger catchments may be associated with lower relief and more streams and wetlands which buffer the effects of changed vegetation cover on water yield.

Changes in runoff must also be considered in the context of other climate change influences. Under CO_2 enrichment, as has been observed over the past 250 years, it is generally accepted that water-use efficiency of plants increases in association with decreasing stomatal conductance. Stomatal conductance is a measure of how open the pores in leaves are. High conductances allow high rates of diffusion of CO_2 into the leaf (for use in photosynthesis) and movement of water out of the leaf. A plant must balance the need for adequate CO_2 with the need to avoid water stress, particularly in arid and semi-arid areas. Where atmospheric concentrations of CO_2 have increased, plants can conserve water by restricting stomatal opening but still obtain enough CO_2. This decrease in stomatal conductance, which equates to a decline in transpiration, will cause increased runoff where vegetation remains structurally unchanged. It is likely that changes in water yield in the early years of woody thickening and the change in water yield after a new thickened equilibrium has been reached many decades later, will differ. Increased yield observed in the short term wil be followed by a decrease back to values similar to those observed prior to thickening, in the later stages.

Reduced grass growth and reduced beef production

With the tendency away from open grassland communities towards more dense woodlands, the availability of grazing land for livestock has declined. Since cattle prefer to graze on grass rather than browse on shrubs, one method suggested for maintaining grazing areas has been to keep domesticated browsers (such as goats) with cattle herds to prevent woody encroachment. It is expected that this strategy would better utilise available vegetation and increase meat production but data for Australian systems are not readily available. The role of grazing in facilitating woody thickening is discussed below.

Other impacts of woody thickening

Remnant vegetation ecosystems are under threat in most parts of the world, including Australia and this is a significant threat to biodiversity. For instance, African savannas support a high diversity of large mammals which depend on the equilibrium between grassland and woody vegetation. Similarly, many of Australia's unique marsupial species rely on remnant vegetation ecosystems for habitat and food supplies.

Biogeochemical impacts of expansion of woody vegetation are not limited to the carbon cycle as the nitrogen cycle is also affected. Nitrogen oxide emissions increase with woody thickening, depending on the volume of above-ground biomass and soil type and are mediated by temperature and precipitation. Nitrogen is an essential nutrient for plant growth and productivity. It is present in all proteins and is an important component of chlorophyll molecules, which are vital for photosynthesis. When nitrogen gas production increases due to woody thickening, the soil stores of nitrogen become depleted and nitrogen may become a limiting nutrient. Furthermore, elevated atmospheric concentrations of NO_2 act as a catalyst in the destruction of atmospheric ozone and thus, woody thickening can have global consequences.

Causes of woody thickening

The process of woody thickening can happen as part of the natural succession of an ecosystem or it can be human-induced. All vegetation continually undergoes recovery after disturbance and an ecosystem will move through phases of the disturbance/recovery cycle. In Australia, where fire, flood and drought are recurrent features of most of the landscape, recovery after disturbance is a commonly observed phenomenon and consequently most vegetation is thickening (recovering) most of the time. Human activities influence this cycle by causing additional disturbances or favouring recovery by removing natural disturbances. For instance, clearing of vegetated land for pasture is a human-induced disturbance, while fire prevention is an example of the removal of a natural disturbance. So, while woody thickening can be a naturally-occurring process, it is clear that it has it also been accelerated through human activities. These are thought to be changes in land-use practice, including changes in fire regime and grazing pressure and the cessation of clearing and abandonment of formerly managed grass and cropland. There is also an increasing awareness of potential roles for climate and changes in atmospheric CO_2 concentration in causing woody thickening (and woody invasion).

Some examples of woody thickening

Study location	Period of study	Technique	Findings	Reference
Southwestern Qld	1951–1994	Aerial photography	Minor increases (<5%) in density of remnant woody vegetation but cleared areas had recovered to almost 60% of their original cover	Witt *et al.* (2006)
Eastern Qld	1982–1995	Permanent monitoring plots across savannas and grazed woodlands	Annual carbon increment of 0.53 t C ha^{-1} y^{-1} across 57 sites and estimated sink of 18 Mt C y^{-1} for above- and below-ground biomass of woodlands studied, extending to 35 Mt C y^{-1} if extended to all thickened grazed woodlands in Qld	Burrows *et al.* (2002)
Qld	1951–1995	Aerial photography	Overstorey cover increased from 25% to 30% with the most rapid growth associated with higher rainfall in 1951–1965	Fensham *et al.* (2005)
Northern Texas, USA	1937–1999	Aerial photography and Landsat data	Unmanaged rangelands had up to 500% increases in woody cover	Asner *et al.* (2003)
USA	1950–1990	Aerial photography	Fire exclusion resulted in 125 Mt C y^{-1} sink from woody thickening	Houghton *et al.* (2000), cited in Gifford and Howden (2001)
Global	NA	Literature review	Conversion of non-woody savannas to closed woodlands represents global carbon sink of 94.3 Pg C	Scholes and Hall (1996) cited in Bond and Midgley [2000]

The causes of woody thickening remain under debate, most likely because site-specific factors play an essential role in governing the rate of vegetation expansion. These site-specific factors may dominate or act in concert with any over-arching global mechanism. Suggested explanations of woody thickening generally involve combinations of changes to fire, grazing and climate regimes. The nature, intensity and interactions between these three factors vary over time and space and hence, identifying the relative importance of each factor is complicated. This is now discussed.

The role of livestock grazing

Livestock grazing certainly plays a role in woody thickening. Sheep and cattle generally graze on grasses while native browsers often include shrubs in their diet. Consequently, displacement of native animals with exotic stock grazers commonly favours shrub growth. Once livestock are established, differences in stock species and grazing pressure across landscapes has been proposed as one of the main factors influencing small-scale patterns and dynamics in vegetation change. Grazing can foster woody thickening directly by reducing competition from grasses and spreading seeds of woody plants, and indirectly-by reducing fuel loads and hence fire frequency and/or intensity. It has been suggested that grazing on saplings of woody species may also suppress woody thickening, facilitating grass production and therefore fire. However, given the current trend in woody thickening, we assume this scenario has a limited impact on the establishment of woody vegetation.

The role of fire

The current role of fire is most likely closely linked to livestock grazing and it is most certainly governed by landscape management practices. Prior to agricultural development, regular anthropogenic fires had apparently been the norm in Australia for thousands of years, keeping ecosystem carbon stocks well below the potential upper limit in many places. Fire reduction regimes imposed after European settlement included control burning to reduce fuel loads, fire-breaks, fire-trails and fire-fighting infrastructure. These practices have reduced the frequency and intensity of fires and have been associated with increasing carbon stocks across many landscapes. The result has been the progressive occupation and thickening by woody plants where they did not exist prior to modernisation. For instance, the exclusion of fire in the United States between 1950 and 1990 has resulted in a sink of 125 Mt of carbon per year from woody thickening. Removal of annual fires in NT savannas has been suggested as a management tool for improving carbon sequestration since shrubs and other woody vegetation provide a carbon storage increment of 1.7 t C ha^{-1} y^{-1} but this is lost when fires release the carbon back into the atmosphere.

When fires do occur, they can still foster growth of woody plants. Woody plant dynamics are density-dependant so recruitment increases when overstorey competition decreases. A canopy fire may damage or remove the overstorey but often this allows the establishment of the next generation of saplings, particularly because altered climate conditions seem to enhance sapling growth as outlined below. Approximately 400 000 ha of land were burnt in Vic. and SA during the Ash Wednesday fires of 1983. Regeneration of the highly flammable Mountain Ash forests in Vic. was stimulated by trees setting seed in the fertile ash which remained after the fires, resulting in a new generation of even-aged forest. Without the removal of the overstorey, there is insufficient light for saplings to grow and in this example, fire fostered woody thickening.

The following discussion is a mechanism that has been suggested for the role of grazing and fire in woody thickening.

During wet periods, shrubs and trees establish among grasses, creating fuel for fires so that when dry periods arrive, fuel is plentiful. Before livestock grazing, natural or anthropogenic fires would have thinned woody vegetation during dry periods, maintaining the savanna structure, excluding invasion of rainforest species which are fire sensitive and thereby maintaining standing woody biomass at levels below those that would occur in the absence of fire. Furthermore, the accumulation of a large biomass in the grass understorey each year also encourages a cycle of fuel build-up followed by an intense burn. Under pastoral management, fire fuel loads are minimised by domestic stock so fires are not as frequent or intense. Thus, grazing removes the major impediment to woody plant recruitment, namely fire.

The role of climate change

Several features of climate change may influence woody thickening, including altered precipitation regimes, rates of mineralisation (particularly nitrogen) and elevated CO_2 concentrations in the atmosphere. Theoretically, changes in rainfall may favour either trees or grasses depending on when and how much rain falls, but research remains sparse. Increased rates of mineralisation fertilises nutrient-poor soils, potentially favouring growth of woody species which have higher rates of productivity and much slower turnover. Elevated CO_2 concentrations may also favour trees over grasses as discussed below.

Two conceptual models have been proposed to explain the role of climate change in stimulating woody thickening. The first postulated that climate change (in particular, increased atmospheric CO_2 concentration and declining evaporative demand) may explain the global phenomenon of woody thickening. The conceptual model was based around six key observations. These are:

1 The concentration of atmospheric CO_2 has increased since the industrial revolution.

2 This increase accelerates the rate of photosynthesis and this increase is larger in C3 plants (that is, trees) than C4 grasses.

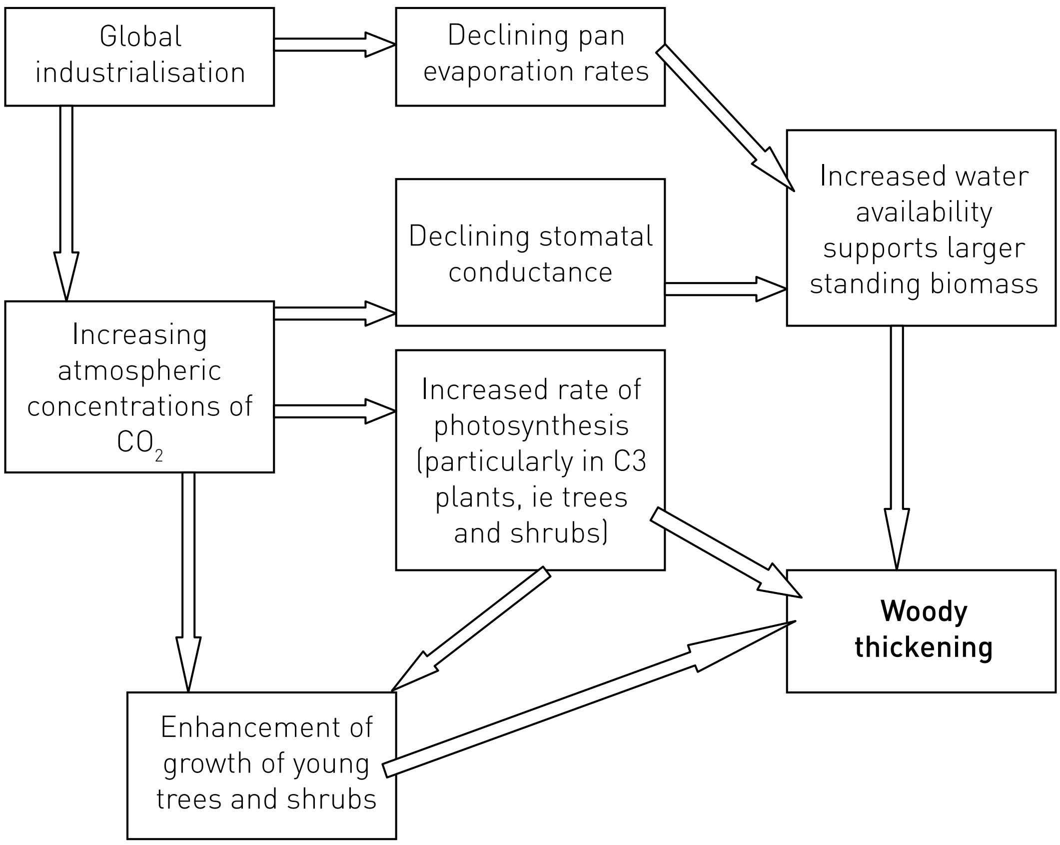
3 Stomatal conductance declines in response to elevated concentrations of CO_2 in the atmosphere.

4 The growth rate of young trees and shrubs is enhanced by CO_2 enrichment and the proportional stimulation of growth is larger in xeric than mesic sites.

5 Pan evaporation rates have declined globally.

6 Because of (3) and (5) above, there is increased water availability in the short-to-medium term which can support a larger standing biomass of woody species, that is, woody thickening.

In addition to the details of this conceptual framework, elevated atmospheric CO_2 has also been shown to increase the water-use-efficiency of plants. In arid and semi-arid grasslands where low soil water availability inhibits the establishment and growth of many woody plants for most of the year, the increased water-use-efficiency of plants under CO_2 enriched conditions can lead to increased soil moisture, reducing water stress and therefore reducing



Conceptual model describing the role of climate change in woody thickening.

water limitation as a significant obstacle to establishment of woody plants. Furthermore, once some trees have established, these act as 'nurse' plants, facilitating the germination and survival of further woody seedlings by providing shade, further reducing water stress. Thus a positive feedback process begins whereby woody vegetation expands rapidly as shade reduces heat and water stress on tree seedlings, increasing the success of woody plants. This is particularly effective under dry conditions.

Suitable locations for initial establishment of woody species are readily available since bare patches of soil are common in semi-arid grasslands due to burrowing animals and low productivity and plant cover. If woody vegetation is unable to establish in grassy areas due to competition for water and in unvegetated areas because of heat and water stress, increasing atmospheric CO_2 concentrations may be able to kick-start establishment of woody vegetation by decreasing water stress.

The second conceptual model considers the role of climate change in conjunction with other disturbances. For woody plants to succeed in moving into grassland, seedlings need to escape injury from fires and grazing animals so adult trees can become fully established. The escape opportunities are governed by intervals between fires and periods of low herbivore intensity. Escape is also influenced by the rate at which woody plants can recover, grow to escape height and avoid canopy-kill. Fast regrowth after fires requires high starch concentrations in the roots. Consequently the best strategy is to store large amounts of carbon in the roots and then allocate this carbon to rapid stem growth, as is commonly observed in the lignotuberous eucalypt (and other genera) species. This strategy is enhanced by increasing atmospheric concentrations of CO_2 since there is more carbon available for storage and use in growth. In savanna areas, many resources are non-limiting. Light is plentiful (unlike a closed forest canopy) and soils are nutrient rich after a fire, so that carbon fixation into biomass can be the limiting factor in savanna ecosystems (assuming water is available). Enrichment of atmospheric CO_2 therefore reduces the carbon limitation and favours the growth of woody species. Furthermore the reduction of water use in grasses under CO_2 enrichment leaves more soil moisture available to deeper rooted trees. This hypothesis does not rest on the differential response of C3 and C4 pathways that is purported by some researchers.

The rate of woody thickening may be decelerated through grazing management, fire control or selective thinning. Consequently adjacent properties may exhibit very different rates of woody thickening because of different management practices.

Other factors

Some researchers have noted that the increase in woody vegetation in Central Queensland savannas over the second half of last century was associated with greater rainfall during that period in comparison to droughts in the first half of the 20th century. This led them to postulate that extended periods of greater rainfall can enhance woody thickening since trees can access the deeper profiles that are recharged during extended periods of wetter weather. Increases in rainfall may enhance woody thickening in some areas but under current climate fluctuations, rainfall changes may also be negative, favouring grasses.

In abandoned agricultural areas, cultivation or grazing ceases when profitability becomes too low. In such cases, the soil is often of poor quality through over-exploitation and consequently grass growth declines, reducing fuel loads and therefore fire frequency, and enhancing shrub recruitment. Conversely, if soil is degraded by salinity then woody thinning may occur and so details of the circumstances of abandoned lands are required to determine the rate of woody thickening or thinning. Even freshly cleared areas can be recolonised by woody species, particularly if the root system is left intact so resprouting (coppicing) can occur.

Exotic shrub invasion is a special case of woody thickening. In Australia there are a number of species which have been introduced by humans and spread by domestic animals, including prickly acacia (*Acacia nilotica*), giant mimosa (*Mimosa pigra*), Parkinsonia (*Parkinsonia aculeate*), mesquites (Prosopis spp.) and Indian jujube (*Ziziphus mauritania*). There are often no natural biological control agents and they are unpalatable for native animals and livestock so these species pose a serious weed threat. There are 2500 species of invasive plants which have become established in the wild across the continent. These cost agriculture over $4 billion annually and the costs to native vegetation and fauna include ecosystem displacement, introduction of pests and diseases and changes in the structure and function of vegetation. One of the most invasive woody weeds is

Parkinsonia which covered 12.4% of the continent in 2006 and is particularly prevalent in semi-arid areas. Originally from Central America, it produces vast numbers of seeds each winter and spring which float down water courses to infest new areas. *Parkinsonia* threatens rangelands and wetlands across the continent, preventing access of stock to watering points, reducing productivity of grasses and providing refuge for feral pigs. Habitat for native animals is lost, wetlands can become clogged or eroded due to *Parkinsonia* growth and watertables can be lowered. Aesthetic, cultural and tourist values of many areas are also affected. Control measures include concentrating on prevention of spread, blade ploughing, chemical application and possibly fire, with followup required to prevent growth of seedlings.

Implications for land owners, industry and government

Woody thickening is generally viewed as having a negative impact on landscapes, particularly by graziers who stand to lose grassland for feeding livestock and water through increased transpiration. Potential positive impacts, however, include larger carbon stores (particularly at drier sites where soil organic carbon stores increase) and amelioration of salinisation of soils by reducing the rise of saline water tables.

The value of woody vegetation to landscapes in Australia cannot be overstated. Expansion of crop and pasture land in Australia over the last 200 years has been associated with declining evapotranspiration (through the processes described above) and increased ground water recharge and streamflow. The increase in water quantity and movement has caused mobilisation of salts causing salinisation of water tables and rivers and leaching of fertilisers into aquifers and even onto the Great Barrier Reef. Over 5 Mha of land are affected by dryland salinity in Australia, most of which is in WA. Before woody vegetation is removed, land managers must consider the potential impacts on water resources. There must be a tradeoff between water availability for other purposes and salt and nutrient balances. Development of practices for sustainable resource management for human and ecosystem needs is required.

Salt scald due to land clearing causing dryland salinity.

Australian woodlands provide other ecosystem services besides prevention and amelioration of dryland salinity. They prevent erosion through soil stabilisation, they capture and store atmospheric carbon, encourage nutrient cycling and regulate water quality and quantity. Biodiversity is enhanced by providing habitat for plant and animal species and can prevent weed encroachment. Woody thickening can contribute to all of these valuable ecosystem services.

Degradation of rangelands due to loss of topsoils or physical and chemical deterioration of soils is often preceded by a reduction in vegetation cover or the biological soil crust. Drivers for this include overgrazing, deforestation, use of woody plants for fuel and climatic variation (such as drought conditions). These processes are further complicated by feedback between climatic and anthropogenic factors. If shrub canopies are reduced or eliminated, less and less water is retained in the landscape through increased runoff, accelerating degradation processes through movement of soil nutrients, leading to feed back loops. We are not yet able to predict how the water cycle is influenced by changes in the structure and composition of native vegetation communities.

Most areas undergoing woody thickening are highly sensitive to change due to scarcity of water and nutrients. We must improve our understanding of hydrological, biogeochemical and ecological processes through interdisciplinary approaches in order to forecast environmental change.

Conclusions

Woody thickening is one of a suite of changes occurring in global vegetation. Factors causing woody thickening vary spatially and temporally and involve interactions between natural and human-induced processes. Atmospheric concentrations of CO_2, and climate (especially rainfall) effect growth and establishment of woody vegetation in arid and semi-arid areas. In addition to these influences, imposed management, particularly intensification of grazing and change in fire regimes are potent triggers for increases in woody vegetation cover and biomass. Woody thickening is an ongoing process which influences carbon storage and fluxes, catchment water balances, other biogeochemical cycling and grass availability for stock grazing.

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Definitions

Arid and semi-arid ecosystems are very dry. They are typified by low annual rainfall (generally less than 500 mm) and high evaporative demand.

Rangelands are uncultivated areas generally covered in native grasses and shrubs. They occur in arid and semi-arid areas.

Savanna ecosystems are made up of trees forming an open canopy over grasses and shrubs. Also known as an open woodland. In monsoonal savannas, grasses die off during the dry season when moisture in the upper profile of the soil become depleted.

Gt, Giga tonnes = 1×10^9 t

Mha, Mega hectare = 1×10^6 ha

Mt, Mega tonnes = 1×10^6 t

Pg, Petagram = 1×10^{12} kg = 1×10^{15} g