

# Effects of afforestation on water yield: a global synthesis with implications for policy

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## Abstract

Carbon sequestration programs, including afforestation and reforestation, are gaining attention globally and will alter many ecosystem processes, including water yield. Some previous analyses have addressed deforestation and water yield, while the effects of afforestation on water yield have been considered for some regions. However, to our knowledge no systematic global analysis of the effects of afforestation on water yield has been undertaken. To assess and predict these effects globally, we analyzed 26 catchment data sets with 504 observations, including annual runoff and low flow. We examined changes in the context of several variables, including original vegetation type, plantation species, plantation age, and mean annual precipitation (MAP). All of these variables should be useful for understanding and modeling the effects of afforestation on water yield. We found that annual runoff was reduced on average by 44% ( $\pm 3\%$ ) and 31% ( $\pm 2\%$ ) when grasslands and shrublands were afforested, respectively. Eucalypts had a larger impact than other tree species in afforested grasslands ( $P = 0.002$ ), reducing runoff (90) by 75% ( $\pm 10\%$ ), compared with a 40% ( $\pm 3\%$ ) average decrease with pines. Runoff losses increased significantly with plantation age for at least 20 years after planting, whether expressed as absolute changes (mm) or as a proportion of predicted runoff (%) ( $P < 0.001$ ). For grasslands, absolute reductions in annual runoff were greatest at wetter sites, but proportional reductions were significantly larger in drier sites ( $P < 0.01$  and  $P < 0.001$ , respectively). Afforestation effects on low flow were similar to those on total annual flow, but proportional reductions were even larger for low flow ( $P < 0.001$ ). These results clearly demonstrate that reductions in runoff can be expected following afforestation of grasslands and shrublands and may be most severe in drier regions. Our results suggest that, in a region where natural runoff is less than 10% of MAP, afforestation should result in a complete loss of runoff; where natural runoff is 30% of precipitation, it will likely be cut by half or more when trees are planted. The possibility that afforestation could cause or intensify water shortages in many locations is a tradeoff that should be explicitly addressed in carbon sequestration programs.

*Keywords:* afforestation, land-use change, plantation, runoff, water yield

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## Introduction

The conversion of natural grasslands to plantations has occurred over extensive areas of the southern hemisphere and will likely continue with new policy and

market incentives to reduce atmospheric CO<sub>2</sub> concentrations. Through the clean development mechanism (CDM), the Kyoto Protocol allows for developed countries to offset part of their CO<sub>2</sub> emissions by establishing carbon-sequestering projects, including reforestation and afforestation. Afforestation has been suggested as a way to simultaneously sequester carbon, increase wood and paper supplies, and diversify rural incomes (Vertessy, 2001). Not surprisingly, the focus of much of the research on this land-use change has been

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on sequestering and storing carbon in the biomass and soils of afforested areas. However, converting grasslands or shrublands to plantations will likely affect many other ecosystem processes, including water yield from rivers and streams (e.g. Duncan, 1995; Dye, 1996; Bashkin & Binkley, 1998; Paul *et al.*, 2002; Jobbágy & Jackson, 2003, 2004; Farley *et al.*, 2004).

Water yield is altered through changes in transpiration, interception, and evaporation, all of which tend to increase when grasslands or shrublands are replaced with trees. Transpiration rates are influenced by changes in rooting characteristics, leaf area, stomatal response, plant surface albedo, and turbulence (Brooks *et al.*, 1997; Hoffmann & Jackson, 2000; Jackson *et al.*, 2001; Vertessy, 2001). Although transpiration is traditionally considered the more important component of forest evapotranspiration (ET), interception and subsequent evaporation from the canopy can also increase substantially, particularly with conifers (Pearce & Rowe, 1979; Cannell, 1999). Evaporation of intercepted precipitation is generally low in grasslands, but can account for 10–20% of rainfall for broadleaf trees and 20–40% for conifers (Le Maitre *et al.*, 1999). The sum of the changes in evaporation and transpiration in plantation catchments leads to an increase in ET (Holmes & Sinclair, 1986); for example, ET from a catchment planted with eucalyptus could be 40–250 mm higher than from a grassland catchment (Zhang *et al.*, 1999). Despite recognition of higher ET rates in plantations, the likelihood that this will reduce water yield has not always been acknowledged (Vertessy & Bessard, 1999), particularly within the context of afforestation programs for carbon sequestration.

Studies of the effect of vegetation change on water yield have focused primarily on the removal of woody vegetation (e.g. Bosch & Hewlett, 1982; although see Scott *et al.*, 2000). Using results from deforestation studies to predict the effects of afforestation may be problematic because they are not necessarily opposite and reversible processes (Robinson *et al.*, 1991). The changes in runoff induced by deforestation and afforestation likely differ in magnitude, timing, and relationship to site characteristics. Deforestation studies are distinguished by factors such as soil disturbance and deposition of slash and litter, which can affect streamflow patterns (Vertessy, 1999). The duration of most deforestation and afforestation studies is also vastly different, and the short time period of the former increases the chance that the effect of rainfall variability will be difficult to separate from the catchment response (Vertessy, 1999). In addition, the timing of changes in runoff may differ significantly, with abrupt changes associated with deforestation and more gradual changes with plantation age following afforestation.

Although the effects of plantation age and rotation length are important for predicting the consequences of afforestation on water yield, these effects are lacking in most studies (Best *et al.*, 2003). A better understanding of the age–runoff relationship after afforestation will allow managers to make predictions using more realistic rotation scenarios – in which a proportion of the landscape is in early growth stages, and full aging is prevented by harvesting. In addition, the effect of afforestation on low flow is an important component of this framework. Changes in low flow may be even more important than changes in annual flow, as the dry season is when reduced water supply will have the most severe effects for users, particularly in arid and semiarid regions (Smith & Scott, 1992; Scott & Smith, 1997; Sharda *et al.*, 1998; Robinson *et al.*, 2003).

In this paper, we quantified the change in streamflow associated with afforestation globally. Our specific objectives were to: (1) assess the direction, range, and extent of changes in total annual streamflow and low flow associated with afforestation, (2) examine the interactions with original vegetation type, tree species planted, plantation age, and climate, and (3) provide a predictive framework for modeling the effects of afforestation on water yield for carbon sequestration scenarios. To accomplish these objectives, we analyzed 26 catchment data sets containing 504 annual observations to assess the effects of afforestation on water yield. These catchment studies included sites that were converted from grassland, pasture, or shrubland to pines, eucalypts, or other species (primarily spruce).

## Methods

### *Data synthesis*

We compiled catchment data sets from peer-reviewed journals as well as reports from governmental and nongovernmental research institutes, representing many parts of the southern hemisphere, as well as India, the UK, and Germany in the northern hemisphere (Appendix A). We examined data from afforested regions with a previous land cover of grassland or shrubland where runoff was measured following planting, and included all the data sets we found with these characteristics. Most of the data were from paired catchment studies, in which streamflow from grassland or shrubland catchments was compared with that of nearby afforested catchments.

We examined the data set for several variables. Most studies reported changes in runoff for several years after afforestation, with some beginning at age 0 and others beginning later in the rotation. The number of years of runoff data varied with each study, with some

studies covering less than a decade and others as much as four decades (Appendix A). For afforested catchments that were harvested after the full rotation length, we included only the data up to the time of harvesting. In cases where data were available from more than one source for the same catchment, we used multiple sources if the information did not overlap (such as covering different time periods or reporting different types of flow data, such as annual vs. low flow). Where they reported the same data for the same time period, we chose those that covered the longest time period and, in some cases, used the additional data sets for supplementary information, such as area planted or calibration period. In no cases were duplicate data from a single catchment used in the analyses. Our database consisted of runoff data for each year reported for a given catchment; for example, where a study included data for plantation ages 1–8, we used each of the 8 years as a data point in our analyses.

The percent of the catchment afforested varied among data sets (Appendix A). In more than three-fourths of the cases, half or more of the catchment was planted, although in three cases it was only 20–40%, and in several cases it was not reported. We based our analyses on the original data sets, uncorrected for the proportion of the catchment afforested, which means that our estimates are conservative, as we are likely underestimating the magnitude of the effects. An alternative used by some researchers is to scale the catchment results by the percentage afforested. To satisfy those researchers, we performed a parallel analysis, scaling all the data to a minimum area planted (75%). For this analysis, all catchments in which less than 75% of the area was planted had the data scaled linearly up to 75% – because it is not typical practice in forestry to plant 100% of a catchment (Scott & Smith, 1997). The data from the catchments for which we lacked information on the area planted were included without scaling. The figures and discussion are based on the unscaled data, but we have included an overview of the analyses using the scaled data in the results section.

The studies included in the data set used one of two general approaches to calculate the change in runoff following afforestation. In ~60% of the data sets, the change in runoff was reported as predicted runoff minus observed runoff. The approach taken in each of these studies to calculate predicted runoff was based on a calibration of runoff between the control and planted catchments before afforestation. Predicted runoff for a given year was calculated based on runoff from the control catchment in that year and the relationship between the control and planted catchments derived from the calibration period. In the remaining ~40% of data sets, the change in runoff was calculated as runoff in the

control catchment minus runoff in the planted catchment. We used the data as the authors presented them.

In the results, we refer to changes in runoff as absolute changes (mm) and proportional changes (% of predicted or control runoff). Because changes in runoff vary from year to year with variations in rainfall, expressing changes as a proportion of expected flow is useful as a way to remove this climatic variability (Scott & Smith, 1997). Not all data sets provided both absolute and proportional runoff values, so some of the data points included in one analysis are absent in the other.

In addition to the change in annual runoff, a number of studies also reported change in low or base flow. Low flow was typically defined in the studies as the flow rate during the driest 3–4 months of the year, or as dry weather summer flow (Smith & Scott, 1992; Scott & Smith, 1997; Sharda *et al.*, 1998; Robinson *et al.*, 2003). In some cases, it was defined more precisely by using an exceedance level (the flow exceeded for a certain percent of the year, generally ranging from 75% to 95%) as a threshold (Fahey & Watson, 1991; Scott & Smith, 1997; Robinson *et al.*, 2003).

#### Statistical analyses

The effect of original (pre-afforestation) vegetation type, plantation species, plantation age, and mean annual precipitation (MAP) on the change in runoff were tested using one-way ANOVAs followed by Tukey's HSD *post hoc* tests; where conditions of normality and homogeneity of variance were not met, nonparametric Kruskal–Wallis tests were used as noted. In each case, the dependent variable was either the proportional change in runoff (%) or the absolute change in runoff (mm) following afforestation. The factors evaluated included original vegetation type (grassland or shrubland), plantation species (pines, eucalypts, or other species), plantation age class (using 5-year intervals), or MAP (<1000, 1000–1250, 1250–1500, >1500 mm). For the analysis of the relationship between change in runoff and plantation age, linear, logarithmic, and quadratic regressions were compared and the curve with the best fit, based on adjusted least-squares regression, was selected. Because we knew, *a priori*, that there should be no change in runoff at age zero, we used regressions through the origin (Zar, 1999). This alters the definition of the  $r^2$  from the more typical  $r^2$  of a regression that is not forced through the origin.

#### Results

Runoff decreased consistently and substantially with afforestation across the entire data set (Fig. 1,  $P < 0.001$ ). More than one-fifth of the catchments experienced

**Table 1** Mean change in runoff ( $\pm$  SE) following afforestation, by original vegetation type and by planted vegetation type, averaged across plantations  $\leq 30$  years old

Afforested from	Afforested to	Change in runoff (%)	Catchment <i>n</i>	Change in runoff (mm)	Catchment <i>n</i>	MAP (mm)	$\Delta$ runoff (mm)/MAP (mm) (%)
Grassland Shrubland	Any species	$-44 (\pm 3)^{**}$	13	$-170 (\pm 13)^{ns}$	11	1241 ( $\pm 16$ )	15 ( $\pm 0.9$ )
		$-31 (\pm 2)^{**}$	8	$-162 (\pm 8)^{ns}$	8	1262 ( $\pm 10$ )	14 ( $\pm 0.6$ )
Grassland or shrubland	Pines	$-35 (\pm 2)^{ns}$	14	$-165 (\pm 8)^{ns}$	14	1236 ( $\pm 10$ )	14 ( $\pm 0.5$ )
	Eucalypts	$-50 (\pm 5)^{ns}$	4	$-173 (\pm 20)^{ns}$	4	1336 ( $\pm 23$ )	14 ( $\pm 1.7$ )
	Other species	$-39 (\pm 7)^{ns}$	3			1415 ( $\pm 33$ )	
Grassland only	Pines	$-40 (\pm 3)^*$	9	$-167 (\pm 13)^{ns}$	9	1260 ( $\pm 18$ )	14 ( $\pm 0.9$ )
	Eucalypts	$-75 (\pm 10)^*$	1	$-202 (\pm 38)^{ns}$	1	1166 ( $\pm 0$ )	19 ( $\pm 3.2$ )
	Other species	$-39 (\pm 7)^*$	3			1415 ( $\pm 33$ )	
Shrubland only	Pines	$-30 (\pm 2)^{ns}$	5	$-163 (\pm 9)^{ns}$	5	1226 ( $\pm 9$ )	15 ( $\pm 0.6$ )
	Eucalypts	$-38 (\pm 5)^{ns}$	3	$-159 (\pm 23)^{ns}$	3	1414 ( $\pm 24$ )	12 ( $\pm 1.9$ )

In order to make differences between grasslands and shrublands and among plantation species comparable, all plantations  $\leq 30$  years old were included.  $\Delta$ runoff/MAP = change in runoff (mm)/mean annual precipitation (mm)  $\times 100$ . Catchment *n* = the number of catchments represented in each category. Significance symbols refer only to comparisons of mean change in runoff among the groups within a category (i.e. grassland vs. shrubland pooled across all tree species; pines vs. eucalypts vs. other species pooled across grasslands and shrublands; and pines vs. eucalypts vs. other species compared within either grasslands or shrublands).

\*\* $P < 0.001$ , \* $P < 0.05$ , ns, not significant. Significance was determined using Kruskal–Wallis tests.

reductions of 75% or more during at least 1 year and 13% of the catchments experienced 100% runoff reductions for at least 1 year (Fig. 1a,c). Both the original vegetation type at a site and plantation species significantly influenced proportional changes in streamflow (Table 1,  $P < 0.001$  and  $P < 0.05$ , respectively). When averaged across ages, annual runoff reductions were greater in grasslands ( $44 \pm 3\%$ ) than shrublands ( $31 \pm 2\%$ ) (Table 1,  $P < 0.001$ ). Eucalypts had a greater impact than pines in sites that were originally grasslands, with runoff reductions of 75% ( $\pm 10\%$ ) and 40% ( $\pm 3\%$ ), respectively (Table 1,  $P < 0.001$ ).

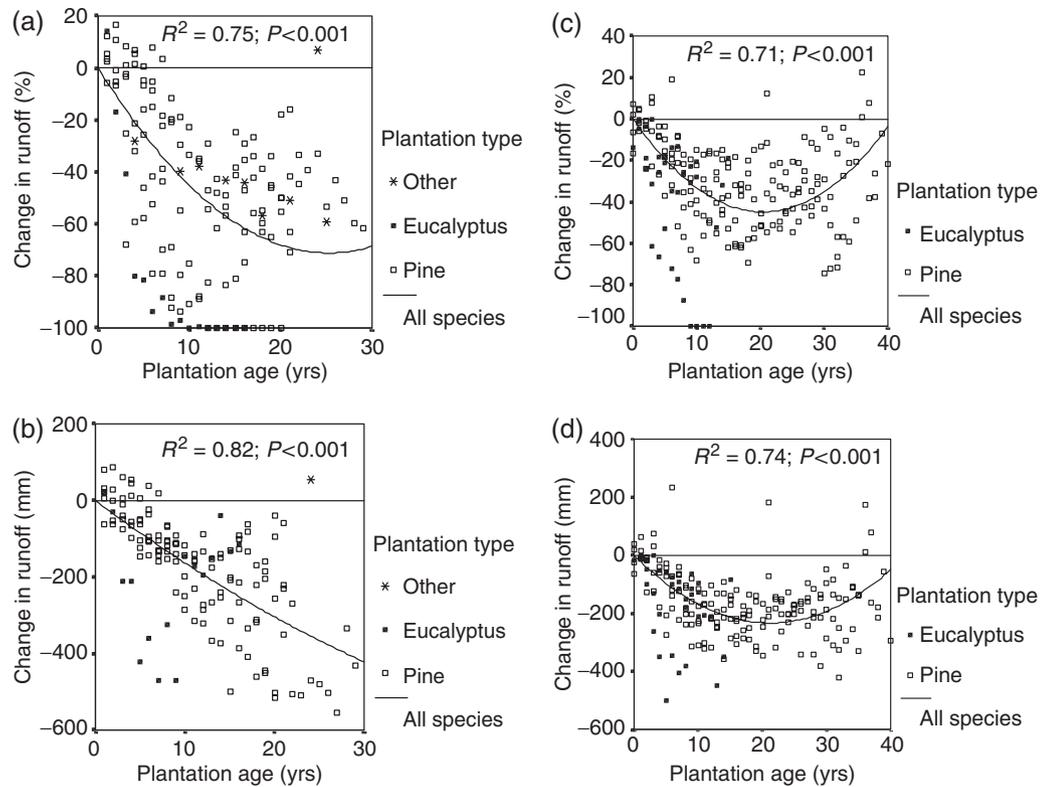
Plantation age strongly affected runoff, whether expressed as absolute or as proportional changes (Table 2; Fig. 1,  $P < 0.001$  in both cases). Runoff reductions in afforested grasslands and shrublands were similar in the first 5 years after tree establishment ( $-16\%$  and  $-15\%$ , respectively), but diverged as the plantations aged (Table 2). Afforested grasslands reached a 50% reduction in runoff by the tenth year, compared with 35% in afforested shrublands at the same age (Table 2). In proportional terms, maximum reductions were reached  $\sim 5$  years earlier and were substantially larger when grasslands were afforested (67% compared with 43% in shrublands, Table 2).

Decreases in streamflow were sustained through 30 years in grasslands and, in absolute terms, showed no sign of recovery with plantation age (Fig. 1b). In proportional terms, there appeared to be some recovery for afforested grasslands after 20 years (Fig. 1a), but most of this is attributed to a single catchment where a defoliation outbreak coincided with several years of

above-average rainfall, after which runoff losses again became more severe (Scott *et al.*, 2000). In contrast, shrublands showed a distinct recovery in runoff after approximately 35 years of afforestation, both in proportional and absolute amounts (Fig. 1c,d). Because eucalyptus rotations are shorter than 35 years, none of the eucalyptus sites in the database extended to the age at which this recovery occurred. However, the data from the grassland sites demonstrated a more complete loss of runoff with eucalypts, with many reaching 100% reductions in streamflow within 10 years (Fig. 1a), suggesting that the trend toward recovery may only apply to shrublands planted with pine.

Afforestation reduced runoff across a broad range of climates (Fig. 2). Reductions in runoff were significantly related to MAP for afforested grasslands in both proportional and absolute terms. For grasslands, the wettest sites (MAP  $> 1500$  mm yr $^{-1}$ ) had the largest absolute reductions ( $-287 \pm 44$  mm) but the smallest proportional reductions ( $-27 \pm 4\%$ ). In contrast, proportional losses were far greater at the driest grassland site ( $-62 \pm 10\%$ ) (Fig. 2), suggesting that the effects of afforestation on water yield will be more severe in drier regions. For shrublands, proportional and absolute reductions were largest at the driest sites (MAP = 1000–1250 mm yr $^{-1}$ , data not shown), but they also were significantly older than the wettest sites, so age may be a confounding factor for the shrubland analysis.

Across the data set, proportional losses in low flow with afforestation were closely correlated with, but even larger than, proportional losses in annual flow (Fig. 3,  $P < 0.001$ ). These data suggest that dry-season losses are



**Fig. 1** (a–d) Proportional and absolute changes in runoff with plantation age, by original vegetation type. The complete data set was used for curve-fitting, but to improve resolution of the figure grassland curves are only displayed to 30 years. Eight points > 40 years are not displayed, clustered around  $-30\%$  and  $-500$  mm (a, b; see Table 2). Regressions were through the origin. Regression equations: (a)  $Y = 0 - 5.636X + 0.112X^2$ , (b)  $Y = 0 - 17.516X + 0.115X^2$ , (c)  $Y = 0 - 4.398X + 0.108X^2$ , (d)  $Y = 0 - 22.044X + 0.520X^2$ .

**Table 2** Mean change in runoff ( $\pm$  SE) following afforestation as a function of plantation age, by previous vegetation type

Age (years)	Grassland		Shrubland					
	$\Delta$ runoff (%)	<i>n</i>	$\Delta$ runoff (mm)	<i>n</i>	$\Delta$ runoff (%)	<i>n</i>	$\Delta$ runoff (mm)	<i>n</i>
1–5	$-16 \pm 5$	35	$-45 \pm 17$	34	$-15 \pm 3^{ab}$	36	$-81 \pm 20^a$	36
6–10	$-50 \pm 6$	36	$-152 \pm 18$	37	$-35 \pm 4^c$	40	$-158 \pm 17^{ab}$	40
11–15	$-67 \pm 5$	30	$-216 \pm 18$	29	$-39 \pm 4^c$	30	$-214 \pm 16^b$	30
16–20	$-58 \pm 5$	29	$-247 \pm 28$	27	$-43 \pm 4^c$	23	$-230 \pm 13^b$	23
21–25	$-42 \pm 6$	12	$-304 \pm 62$	10	$-35 \pm 4^{bc}$	20	$-168 \pm 22^{ab}$	20
26–30	$-54 \pm 4$	4	$-456 \pm 48$	4	$-32 \pm 4^{abc}$	20	$-193 \pm 20^b$	20
31–35					$-38 \pm 6^c$	17	$-203 \pm 26^b$	17
36–40					$-12 \pm 8^a$	8	$-80 \pm 56^a$	8
41–45	$-36 \pm 7$	3	$-669 \pm 103$	3				
46–50	$-27 \pm 2$	5	$-526 \pm 31$	5				
<i>P</i> <	0.001*		0.001*		0.001		0.001	

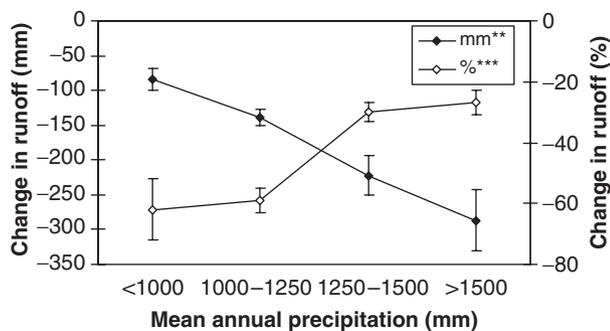
Significance was determined using one-way ANOVAs followed by Tukey's HSD *post hoc* tests, where conditions of normality and homogeneity of variance were met; within each of those columns, means followed by different letters are significantly different from each other at  $P \leq 0.05$ .

\*Kruskal–Wallis tests were used.

*n* = the number of runoff measurements in each age interval (taken from all catchments in which that plantation age range was represented).

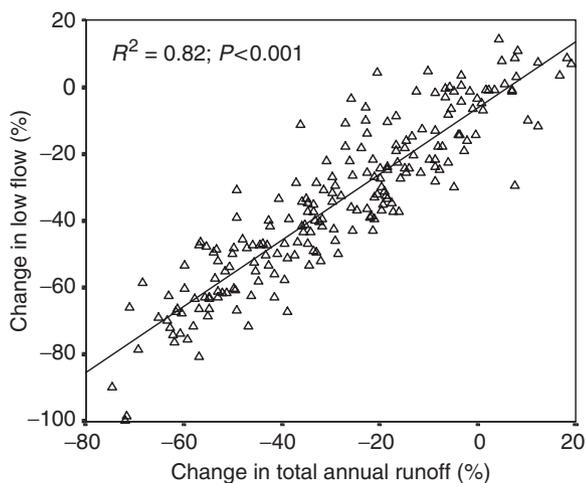
predicted to be even more severe than total annual losses for afforestation scenarios, possibly leading to shifts from perennial to intermittent flow regimes in dry-

region streams. In proportional terms, low flow declined with plantation age through approximately 25 years and then began to recover somewhat (Fig. 4a, b). However,



**Fig. 2** Mean change in runoff ( $\pm$  SE) following afforestation as a function of mean annual precipitation for sites that were originally grasslands. The low precipitation sites were comprised of slightly but not significantly younger stands than the wettest sites.

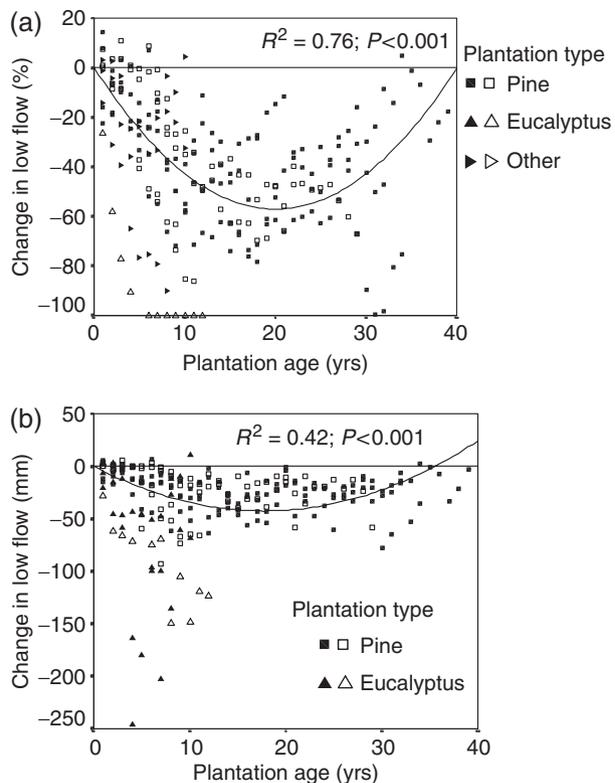
\*\*\*  $P < 0.001$ , \*\*  $P < 0.01$ .



**Fig. 3** Relationship between the change in low flow and the change in total annual flow. Regression equation:  $Y = -6.161 + 0.990X$ .

the recovery may be species specific, as the loss of low flow appears to be more complete for eucalyptus and other species than for pines (Fig. 4a). The pattern of decline and recovery may also occur with the absolute change in low flow (Fig. 4b), although the effect in the first 10–15 years following afforestation was highly variable, ranging from an increase of  $\sim 10$  mm to a decrease of almost 250 mm.

Scaling the data to 75% cover affected the magnitude of the changes in streamflow somewhat, but did not alter the patterns with plantation age, climate, or vegetation type. The change in magnitude was most notable when looking at single year runoff reductions; when data were scaled, one-third (rather than one-fifth) of the catchments experienced reductions of 75% or more during at least 1 year. The effect of scaling was fairly uniform across vegetation types, as average reductions were approximately 5 percentage points higher with scaling



**Fig. 4** (a, b) Change in low flow (% and mm) with plantation age. Open symbols denote sites that were originally grasslands, closed symbols were originally shrublands. Regressions were through the origin. Regression equations: (a)  $Y = 0 - 5.694X + 0.142X^2$ , (b)  $Y = 0 - 4.799X + 0.135X^2$ .

(e.g. 45% rather than 40%) for grasslands or shrublands and for eucalyptus or pine. The relationship between plantation age and runoff reductions was not altered substantially by scaling, particularly for young plantations; in the first 5 years after afforestation, runoff reductions were only 1 percentage point higher. For afforested grasslands, scaling had little effect on maximum reductions, but maximum runoff reductions in afforested shrublands reached 50% after scaling (compared with 43% without scaling). The pattern of runoff reductions across climatic zones also remained largely unchanged with scaling, and it had a minor effect on the magnitude of runoff reductions; scaling had no effect on either absolute or proportional runoff reductions for the wettest sites, but increased the average runoff reductions in the driest sites from 62% to 66%.

## Discussion

Our analysis clearly demonstrates that afforestation of grasslands and shrublands will typically result in a loss of one-third to three-quarters of streamflow on average. Runoff reductions are attained very rapidly after

afforestation, with losses of more than 10% of streamflow occurring in the first 2–3 years after tree establishment for most catchments. This indicates that the lag time between planting and runoff response is usually short, although the full effect on runoff may not occur for one or more decades.

Mean annual rainfall is one of the most important determinants of annual runoff and can have a strong influence on change in runoff after vegetation change (Vertessy, 2001; Zhang *et al.*, 2001). In agreement with previous analyses (Bosch & Hewlett, 1982), our data show that vegetation change has the largest absolute impacts on runoff in high-rainfall areas. However, it also reveals the opposite trend for proportional changes, which may be a better measure of the effects on water supplies and are largest in dry areas (Fig. 2). The reason for the more extreme reductions in drier regions may simply be that there is less water in those systems; for a given proportional increase in ET, the effect on runoff will be larger in drier regions because the fraction of precipitation that reaches streams is already low. Rooting depth may also be a factor, as it is expected to play a particularly important role in increasing ET in dry climates (Zhang *et al.*, 2001; Schenk & Jackson, 2002). As this source of increased water use is likely to persist over the length of a rotation, it could result in larger proportional runoff reductions overall in dry regions.

While runoff reductions occurred across many sites and species, afforestation had a greater effect on runoff in grasslands than in shrublands. The reason for higher runoff reductions in afforested grasslands compared with shrublands may be inherently higher runoff with herbaceous cover. Calder (1986) noted that transpiration losses from scrub vegetation in India tend to be relatively high, with such vegetation using twice as much soil water and drying the soil to twice the depth of annual crops. Contributing to this effect is the difference in the depth and distribution of roots among vegetation types, which is altered by the shift from grasses or shrubs to trees (Jackson *et al.*, 2000). Shrubs have greater similarity to trees, in terms of total root biomass and maximum rooting depth, than to grasses (Jackson *et al.*, 1996); for this reason, the change in access to water and the change in transpiration rates are not likely to differ as much between shrubs and trees as they do between grasslands and trees. In addition, shrubs may be characterized by a longer active transpiration period than seasonally dormant grasses, contributing to total annual transpiration that is higher than that of grasses and more similar to that of trees. As a result, runoff reductions may be less severe when shrublands are afforested relative to grasslands.

These differences between pre-afforestation vegetation types carried over to the age–runoff relationship of afforested grasslands vs. shrublands. When grasslands

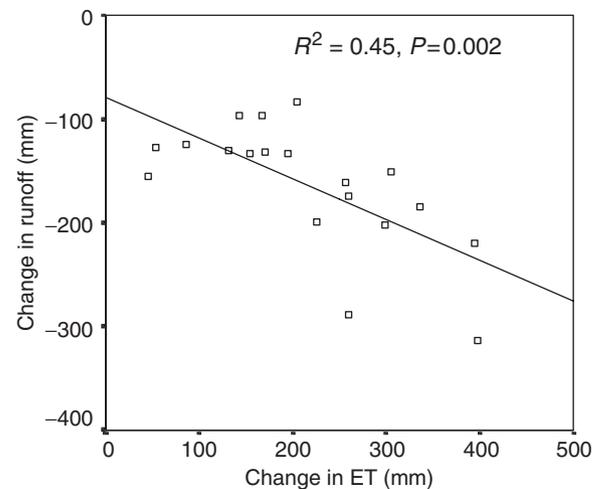


Fig. 5 Change in runoff as a function of change in evapotranspiration (ET). All sites in this data set, which included plantation ages ranging from 0 to 20 years, were originally grasslands.

were afforested, runoff reductions occurred earlier, were larger, and were sustained for a longer period of time than in shrublands. This may result from differences in the underlying causes of the change in ET that leads to lower runoff. The two primary causes of the increase in ET following afforestation are the greater capacity for water loss associated with higher leaf area indexes (LAIs) of the higher stature vegetation (Calder, 1986) and better access to water sources, through accessing of deep water or drawing on stored soil water (Calder *et al.*, 1993; Zhang *et al.*, 2001; Engel *et al.*, 2005). When grasslands are afforested, deep water access likely plays an important role, as there should be a large change in rooting depth (Jackson *et al.*, 1996). This idea is supported by the fact that ET increases more than runoff decreases in grassland sites. In the few studies in our data set (all originally grasslands) where changes in ET were measured in addition to change in runoff, a fairly strong relationship was revealed (Fig. 5,  $R^2 = 0.45$ ;  $P < 0.001$ ). The relationship was not 1 : 1, however, as ET increased more than runoff decreased. While it is unclear whether this occurs in all plantation types or how long this pattern could be maintained, it suggests the use of deep water to subsidize the increase in ET in afforested grasslands. In contrast, when shrublands are afforested, the change in rooting depth is not as large, so that the dominant mechanism behind increasing ET at those sites may be the increased capacity for water loss by the trees relative to shrubs. This mechanism is also likely to be more a feature of younger plantations – occurring as the LAI increases and declining as the tree canopy ages – so that with time the water use of the plantation may approach the control and runoff could begin to recover.

In addition to differences between afforested grasslands and shrublands, there were significant differences between pines and eucalypts in cases where the original vegetation was grassland. Eucalypts caused larger proportional changes in annual runoff than pines did and also appeared to cause more severe and complete losses of low flow within the first 10–15 years after afforestation. Differences in the growth patterns between pines and eucalypts likely play a role in producing these differences. Decreases in runoff following afforestation are positively related to the growth rate of the planted stands (Bosch & Hewlett, 1982), with evidence suggesting that the rate of increase in ET is more rapid under eucalypts because of their rapid early growth and canopy closure (Dye, 1996). This rapid increase in ET should correspond to larger reductions in runoff under eucalyptus in the early part of the rotation. Although growth will begin to slow as the stands age, eucalyptus rotations tend to be relatively short compared with pine, so that overall average water use per rotation is higher (Bosch & von Gadow, 1990), resulting in greater overall runoff reductions. While there is likely to be some variation in species effects by region, generalizations regarding the effects of different plantation species on runoff should be useful for planning afforestation projects and the tree species that will be used in them.

Important interactions may also exist between plantation species and climate, with different plantation types having more severe effects on runoff under different precipitation regimes. In our data set, both eucalypts and pines had their greatest relative impact in lower rainfall regions. However, the two types of plantations differed markedly in terms of absolute reductions. Eucalypts averaged across all ages up to 30 years in the data set produced the smallest runoff reductions ( $90 \pm 14$  mm) in high rainfall zones (MAP > 1500 mm); for pines, the largest runoff reductions ( $189 \pm 40$  mm) occurred in higher rainfall regions. This pattern may be explained by the relative importance of increases in wet canopy evaporation vs. transpiration for different species and in different climatic zones. Interception storage and evaporation from the canopy are thought to be greater for needle-leaved than for broad-leaved trees (Zinke, 1967; Cannell, 1999); the dense canopies of conifers allow for higher canopy storage of rainfall and can lead to large interception losses (typically ranging from 15% to 24%, and in some cases reaching as much as 60%; Le Maitre *et al.*, 1999). For eucalypts, which tend to establish deep roots at a young age (Dye, 1996), higher transpiration is likely the more important component of increasing ET following afforestation (Vertessy, 2001). In addition to differing among tree species, evaporation and transpiration also play different roles under different climate regimes. In higher rainfall zones, evaporation of intercepted rainfall is

the more important component of increasing ET (Holmes & Wronski, 1981; Duncan, 1995), while in drier regions the ability of the vegetation to reach and exploit deep soil water stores to maintain transpiration is an important determinant of changes in water yield (Pearce & Rowe, 1979). Therefore, in drier regions, where transpiration is the more important contributor to absolute increases in ET following afforestation (Scott & Lesch, 1997), eucalypts are likely to cause more severe runoff reductions. In wetter regions, where interception plays a more important role, pines may cause more severe runoff reductions. These differences can have important implications for decisions about where plantations are established and which tree species are used.

#### *Implications for policy*

Our analysis shows that general relationships between plantation age and runoff responses exist. Streamflow response to afforestation can be expected to be very rapid (within 5 years of planting), maximum runoff reductions can be expected between 15 and 20 years after planting, and runoff reductions will likely be larger and more sustained when grasslands are afforested than when shrublands are. These differences among the areas in which afforestation is considered a potential land use are important in planning where plantations should be located, as well as which species should be used. In addition, a better understanding of the timing of the most extreme reductions in runoff may help water managers in their planning. For example, given that the effect of afforestation on low flow is somewhat larger than on total flow, this may be an important variable to incorporate as a guide for afforestation zoning (Scott & Smith, 1997).

Our results also indicate that some past perceptions about where afforestation projects should best be located in order to minimize effects on runoff may be misleading. Specifically, the assumption that changes in runoff will be less severe in low rainfall areas does not hold true when proportional runoff reductions are considered. While it has been suggested that some of the negative hydrologic impacts of afforestation could be minimized by establishing plantations in lower rainfall zones (Vertessy, 2001), our data indicate that this prescription would be unlikely to ameliorate runoff reductions and may actually result in more severe local impacts. This information may be critical for zoning of afforestation projects, in particular in semiarid regions.

The ability to predict the likely effects of afforestation in specific locations with limited information will be the biggest challenge to zoning and planning for these projects. Catchment data are collected over decades and are unavailable for many regions of the world.

However, some indicators, such as the change in runoff as a percent of MAP at a site, may provide a gauge of the probable severity of the loss of runoff. The average ratio tended to be around 14–15% of MAP for most cases in our synthesis (Table 1), and was surprisingly conservative, regardless of whether the sites were originally grasslands or shrublands (15% and 14%, respectively) and whether they were planted to pine or eucalyptus (14% for both) (this value also coincides well with the difference in ET between forest and grassland as a percent of MAP in the curves described in Holmes & Sinclair, 1986). From this we can conclude that, *on average*, trees are able to use approximately 15% more precipitation than grasses or shrubs. This suggests that, in a region where natural runoff is in the range of 10% of MAP, afforestation can be expected to result in a complete loss of runoff; where natural runoff is 30% of precipitation, it could be reduced by half or more when trees are planted. The percent of precipitation used by trees may be higher than 15% in some regions (e.g. grasslands planted to eucalyptus; see Table 1), but this value can serve as a useful indicator for land managers and policy makers in guiding the location of plantations with respect to the demand for water resources.

### Conclusion

The environmental 'co-effects' of afforestation programs have received much less attention than the carbon sequestration potential. However, one of the so-called 'crunch issues' that have been debated in determining how to implement land-use change and forestry projects within the CDM is their potential impact on local livelihoods and environments (Pedroni, 2003). Our synthesis clearly indicates that a reduction in runoff can be expected with afforestation of grasslands and shrublands, which will have ecological and socioeconomic ramifications. In some locations, such as parts of Australia where lower runoff can ameliorate salinity and groundwater upwelling, this will be a positive change. In many other regions, reduced runoff will cause or intensify water shortages, a tradeoff that should be explicitly recognized before land conversion.

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## Appendix A

See Table A1 for catchment data sets used in the synthesis.

Table A1 Datasets used in the synthesis

Source	Name of site(s)	Location	Latitude/ longitude	MAP (mm)	Original vegetation	Plant species	Plantation age (years)	Percent planted	Data type	Notes
Borg <i>et al.</i> (1988)	Padbury Reservoir	Southwest Australia	N/A	880	Crops and pastures	<i>Pinus radiata</i> , <i>Eucalyptus globulus</i> <i>P. patula</i>	3–8	70	P–O	
Bosch (1979)	Cathedral Peak II	Winterton, Natal Drakensberg, South Africa	29°00'S/29°15'E	1400	Grassland		1–26	52	Supp	
Calder & Newson (1979)	Wye and Severn rivers, Plynilimon	Wales, UK	N/A	2350	Pasture	<i>Picea sitchensis</i> (80%)	43–50	100	C–P	Planting from 1937 to 1964; 1937 used to calculate plantation age
Dons (1986)	Tarawera	North Island, New Zealand		1500	Scrub and native bush	Pine	Average for 1–18	28	C–P	MAP estimated from graph
Dons (1987)	Purukohukohu	North Island, New Zealand	38°26'S/176°13'E	1550	Pasture	<i>P. radiata</i>	Average for 8–11	N/A	C–P	
Duncan (1995)	C14	Moutere Gravel hill country, Nelson, New Zealand	N/A	1020	Pasture	<i>P. radiata</i>	1–21	N/A	C–P	
Fahey & Jackson (1997)	Glendhu	Waipori River, Otago, New Zealand	45°50'S	1350	Tussock grassland	<i>P. radiata</i>	9–12	67	C–P	
Fahey & Watson (1991)	Glendhu	Waipori River, Otago, New Zealand	45°50'S	1355	Tussock grassland	<i>P. radiata</i>	1–8	67	C–P	Catchment was contour-ripped to 60 cm depth prior to planting
Mwendera (1994)	Luchelemu River	Malawi	11°45'S/33°50'E	1300	Montane grass and scrub	Pine and eucalyptus	Mean	93	C–P	Low flow only
Nämmi (1970)	Cathedral Peak II Cathedral Peak III	Winterton, Natal Drakensberg, South Africa	28°00'S/29°15'E	1660	Grassland	<i>P. patula</i>	1–16	75	Supp	Planting of CP II began in 1951, but not finished until 1961
Robinson (1998)	Coalburn	Northwest England	N/A	1350	Grassland and bog	Sitka spruce	24	N/A	C–P	
Robinson <i>et al.</i> (1991)	FM/N/ FM/S	Chiemseemoors, Germany	47°48'N/12°26'E	1440	Bog formerly used for agriculture	Norway spruce	4–25	N/A	P–O	
Samraj <i>et al.</i> (1988)	Glenmorgan, Ootacamund	Nilgiri Plateau, South India	11°28'N/76°37'E	1535	Grassland and woodland	<i>E. globulus</i>	1–10	59	P–O	
Scott & Lesch (1997)	Mokobulaan A Mokobulaan B	Lydenburg, Mpumalanga, South Africa	27°17'S/30°34'E	1135 1170	Grassland Grassland	<i>E. grandis</i> <i>P. patula</i>	1–17 1–21	100 100	Supp	

(Continued)

Table A1 (Contd.)

Source	Name of site(s)	Location	Latitude/ longitude	MAP (mm)	Original vegetation	Plant species	Plantation age (years)	Percent planted	Data type	Notes
Scott <i>et al.</i> (2000)	Westfalia D	Tzaneen, Mpumalanga, South Africa	23°43'S/30°04'E	1250	Scrub	<i>E. grandis</i>	1–15	83	P–O	Scrub forest cleared before planting
	Mokobulaan A	Lydenburg, Mpumalanga, South Africa	27°17'S/30°34'E	1170	Grassland	<i>E. grandis</i>	1–22	97		
	Mokobulaan B	Winterton, Natal Drakensberg, South Africa	28°00'S/29°15'E	1180	Grassland	<i>P. patula</i>	1–20	95		Controlled burn before planting
	Cathedral Peak II	Jonkershoek, Western Cape, South Africa	33°57'S/18°15'E	1400	Grassland	<i>P. patula</i>	1–29	75		
	Cathedral Peak III			1515	Grassland	<i>P. patula</i>	1–22	86		
	Bosboukloof			1125	Fynbos shrubland	<i>P. radiata</i>	5–38	57		
	Biesievlei			1300			1–35	98		
	Tierkloof			1320						
	Lambrechtsbos B			1145			1–40	36		
	Lambrechtsbos A			1125			1–32	82		
							1–18	89		
Sharda <i>et al.</i> (1998)	Glenmorgan, Ootacamund	Nilgiri Plateau, South India	11°28'N/76°37'E	1535	Grassland and woodland	<i>E. globulus</i>	1–10	59	P–O	Second rotation
Smith (1987)	Taiieri River (Jura Creek)	East Otago, South Island, New Zealand	N/A	1000	Pasture	<i>P. radiata</i> , <i>P. nigra</i>	N/A	N/A	C–P	Catchments cleared of native grasses and shrubs, planted with pasture or pine
Smith (1992)	Moutere Hills	Nelson, New Zealand	41°22'S/173°04'E	1050	Pasture (ryegrass)	<i>P. radiata</i>	5–9	20	P–O	
Smith & Scott (1992)	Westfalia D	Tzaneen, Mpumalanga, South Africa	22°43'S/30°04'E	1600	Scrub	<i>E. grandis</i>	1–8	83	P–O	Low flow data
	Mokobulaan A	Lydenburg, Mpumalanga, South Africa	24°17'S/30°34'E	1150	Grassland	<i>E. grandis</i>	1–12	100		
Van Wyk (1987)	Mokobulaan B	Jonkershoek, Western Cape, South Africa	33°57'S/18°15'E	1150	Grassland	<i>P. patula</i>	1–11	95		
	Bosboukloof			1300	Fynbos	<i>P. radiata</i>		57	Supp	
	Biesievlei			1425				98		
	Tierkloof			1800				36		
	Lambrechtsbos B			1475				82		
	Lambrechtsbos A			1415				89		

Data type refers to the way in which the data were used in the synthesis: data were either reported and used as predicted–observed runoff (P–O) or as control catchment–planted catchment runoff (C–P); some data sets were only used for supplementary information (e.g. planted area, year of plantation, etc.) (Supp). Plantation age refers to the range of plantation ages reported for a given catchment. MAP, mean annual precipitation; N/A, not available.