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Jerome K. Vanclay
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Managing water use from forest plantations

Jerome K Vanclay

Southern Cross University

PO Box 157 Lismore NSW 2480

Tel +61 2 6620 3147, Fax +61 2 6621 2669, JVanclay@scu.edu.au

Abstract

Tree plantations have developed a reputation for excessive water use, with age commonly used as an explanatory variable to predict water loss – but many factors have the potential to affect plantation water use, and few of these alternatives have been considered. Changes in forest cover may be correlated with other environmental changes that may affect precipitation, transpiration, and runoff, indicating that more thorough investigation is required in both field and simulation studies. Several factors influencing water use by plantations are amenable to management control, so there is scope to design and manage forest plantations deliberately for water use efficiency. Research is needed to elucidate the relative contributions of forests and grasslands to atmospheric moisture; the influence of vegetation on the distribution of rainfall; the effect of air turbulence from plantation edges, firebreaks and streamlines; the potential to modify atmospheric coupling of forest plantations through plantation design, the use mixed species plantations, and by softening hard edges by thinning and pruning plantation edges.

Key words: Runoff, infiltration, evapotranspiration, roughness, atmospheric coupling

Introduction

Water use by plantations has received prominent attention in many circles in recent years (Andreassian, 2004; Farley et al., 2005; Jackson et al., 2005; Brown et al., 2007; Dijk and Keenan, 2007; Dijk et al., 2007; Dye and Versfeld, 2007), but the evidence presented remains equivocal. Much of the discussion in Australia (e.g., Keenan et al., 2006) accepts the current paradigm without sufficient regard for the uncertainties. This paper re-examines some of these assumptions, highlights issues that warrant further research, and draws attention to ways that forests may be managed to minimize water loss. This paper makes no attempt to comprehensively present all the 'plantations versus water' literature which is well covered in recent reviews (e.g., Vertessy et al., 2001; Brown et al., 2005; Farley et al., 2005; Jackson et al., 2005; Benyon et al., 2007; Dijk and Keenan, 2007). Instead, it seeks to complement those reviews by re-examining equivocal elements and offering alternative interpretations that warrant further investigation.

Literature

Recent reviews (Vertessy et al., 2001; Brown et al., 2005; Farley et al., 2005; Jackson et al., 2005; Benyon et al., 2007; Dijk and Keenan, 2007) have postulated that water yield from afforested catchments declines with increasing plantation age, specifically through the relationship with leaf area index (Watson et al., 1999). In Australia, the correlation between age of regrowth and water yield is often attributed to Kuczera (1987), but others had earlier noted a correlation between the basal area of regrowth and water yield (e.g. Kovner 1956). This relationship with forest age appeals to many people because the assumed trend reflects the typical pattern of tree growth and invites the implicit assumption is that faster growth must require more water (e.g.,

Spring et al., 2005). However, very little of the water used by plantations is assimilated as carbohydrate (Kozlowski, 1982); most is transpired to the atmosphere as water vapour. This popular view is contrary to local knowledge in many places (Wilk, 2000), and overlooks the alternative explanation that tall dense canopies have strong aerodynamic coupling and high evapotranspiration (Goldberg and Bernhofer, 2001). So the question that remains is why hydrological dynamics change after plantation establishment, and what alternative explanations warrant exploration. In many cases, this question is posed in the context of afforestation of agricultural land, but it also applies in analogous situations (regrowth following wildfire or timber harvesting) and the converse situation of deforestation.

One possibility is that it is not the tree plantation *per se*, but other aspects of the change in land use that influences hydrology and changes the pattern of runoff. For instance, it has long been known that grazing causes soil compaction and reduces infiltration (e.g., Dunford, 1949; Rauzi and Hanson, 1966; Trimble and Mendel, 1995; Mwendera and Mohamed Saleem, 1997; Hiernaux et al., 1999; Chandler, 2006), and that the removal of grazing can lead to a reduction in runoff (e.g., Hamza and Anderson, 2005). In addition, most plantation establishment involves actively modifying the soil to reduce runoff and improve infiltration (Evans and Turnbull, 2004; Ilstedt et al., 2007). It is logical that these changes to the soil may affect hydrology and affect both base and peak flows (Guillemette et al., 2005; Waterloo et al., 2007). This effect would appear to operate at a time-scale commensurate with the alleged age-dependent water use trend, but relatively few publications have examined the potential interaction of land use history on the runoff (e.g., Ferreira et al., 2005; Zimmermann et al., 2006).

Another possible explanation arises from weaknesses in paired catchment studies, which remain the mainstay of many hydrology studies. Many paired catchment studies rely on simplistic assumptions of rainfall distribution to infer the rainfall in both catchments, and may lack sufficient replication or control of treated and untreated watersheds (Blackie and Robinson, 2007). Many limitations have been examined (e.g., Blöschl et al., 2007; Brown et al., 2005; Cosandey et al., 2005; Lane et al., 2005; Liu et al. 2003; Stednick, 1996; Watson et al., 2001) but the possibility that rainfall patterns may change after de- or re-forestation in one of the catchment pairs is rarely entertained. Evidence suggests that land use can influence rainfall within substantial neighbourhoods (Anthes, 1984; Trenberth, 1998, 1999; Bornstein and Lin, 2000; Pielke, 2001; Shepherd and Burian, 2003; Bruijnzeel 2004; D’Almeida et al., 2007), and that regional recycling of rainfall can be significant (Raddatz, 2000; Bosilovich and Schubert, 2001). Empirical reports indicate that deforestation in the Amazon (Nobre et al., 1991; Rocha, 1996; Moreira et al., 1997; Marengo, 2006; Trancoso, 2007) and in equatorial Africa (Kunstmann and Jung, 2003; Roy et al., 2005) has changed local climate, and theoretical studies support this notion (Makarieva et al., 2006; Makarieva and Gorshkov, 2007). So it is likely that paired catchments may not be independent (in an experimental sense) and may affect the rainfall in the adjacent pair (Pielke et al., 2007). Reviews have not eliminated the possibility that rainfall may emulate the “tragedy of the commons” (Hardin, 1968) with forested catchments transpiring the most moisture while non-forested catchments receive a disproportionate share of rainfall. This may occur in situations where precipitation originates as evapotranspiration (rather than as evaporation from open water), and may confound simple paired-catchment comparisons.

Several studies in Australia (e.g., Peel et al., 2000, 2003) rely on the Macaque model (Watson et al., 1999), a model with the unconventional characteristic that the two largest flows (precipitation and transpiration) are exogeneous: precipitation falls from and transpiration disappears into the sky, with no attempt to examine possible connectivity of feedback and rainfall recycling, which may be substantial (Brubaker et al., 1993; Burde and Zangvil, 2001; D'Almeida et al., 2006). Other researchers have commented on the significance of this feedback at various scales (e.g., Makarieva et al., 2006; Molen et al., 2006; Gordon et al., 2008). This deficiency casts doubt on the reliability of some predictions.

Managing forests to minimize water loss

This wide-ranging review of the literature offers sufficient evidence to challenge the accepted paradigm that the reduction in runoff is due to plantation age, to support the possibility of alternative explanations, and to suggest the possibility to manage plantations to reduce water loss. How then, might plantations be managed to reduce water use?

The Penman-Monteith equation is a well-established approach to estimating plant water use (Irmak et al., 2005; Cleugh et al., 2007), and it is easy to conduct a few simple simulations to show that water use by a crop depends strongly on windspeed and atmospheric coupling (e.g., Díaz et al., 2007), both of which may be influenced through forest management. However, few studies of plantation water use take windspeed into account (e.g., Cannell, 1999). Several authors (e.g., Andreassian,

2004; Blanken and Black, 2004; Buytaert et al., 2007) have observed the correlation between leaf area index and coupling. Blanken and Black (2004) observed that seasonal changes in the structure of deciduous forests had a significant effect on coupling and canopy conductance, and Schellekens (2000; Schellekens et al., 2000) has observed the effect of hurricane damage in modifying the canopy roughness and transpiration of tropical forests. The utility of wind breaks has long been recognized in the horticultural and agricultural sectors (Kort, 1988; Cleugh, 1998), but forest managers appear to have neglected the possibility to incorporate windbreaks into their plantation design, despite evidence that transpiration is greater at plantation edges (Taylor et al., 2001). Tree species vary greatly in their ability to regulate water loss through stomatal control (Jones, 1998; Whitehead and Beadle, 2004) and canopy characteristics (Komatsu et al., 2007), and a carefully chosen species could provide an effective windbreak to reduce water loss from timber plantations.

Another possibility to control water use is to design the plantation canopy to maximize decoupling by managing canopy roughness (Calder, 1997; Hollinger et al., 2002) and air turbulence induced by abrupt plantation edges and firebeaks (Zhang et al., 2007). There are some indications (e.g., Forrester, 2007) that mixed species plantings may have a canopy structure that is less coupled to the atmosphere, and which may thus reduce transpiration. This may help explain some of the “many unresolved issues about water use from fragmented, heterogeneous vegetation” (Roberts, 2007; similar observation by Bruijnzeel, 2004). It seems likely that plantation prescriptions requiring that streamlines remain unplanted may be counter-productive (e.g., FIFWA, 2006; requires 6 m buffer from watercourse), because it

seems possible that the turbulence induced by the irregular canopy may lead to greater water losses than if water courses were planted with selected native species.

Research needs

This review has highlighted several research needs:

- Where does rain come from: what is the relative importance of moisture transpired from vegetation and evaporated from the sea? What are the relative roles of forests and grasslands in contributing to atmospheric moisture? These questions can be examined using stable isotope analysis of rainwater (Gat, 1996; Moreira et al. 1997; Helliker and Ehleringer, 2000; Wang and Yakir, 2000; Darling and Talbot, 2003; Yopez et al., 2003; Yang et al., 2005; Farquhar et al. 2007).
- How does vegetation affect the distribution of rainfall, and can rainfall be influenced through vegetation management? This issue can be examined using existing data from weather radar (e.g. Zhijia et al., 2004). Such analyses may help improve interpretations of paired catchment studies.
- How is transpiration affected by air turbulence near plantation edges, firebreaks and streamlines? This can be examined through field studies of sap flux density (Herbst et al., 2007; Schiller et al., 2007) in existing plantations.
- Can atmospheric coupling of forest plantations be modified through plantation design, for example by using mixed species plantations to alter canopy roughness? Armbruster et al. (2004) also identified the hydrology of mixed stands as a research need. This topic is amenable to investigation with sap-flow measurements (Oltchev et al., 2002) and eddy-covariance flux

measurements (Kurpius et al., 2003; Blanken and Black, 2004; Zhang et al., 2006) in existing mixed-species plantings.

- Can existing plantations be made more water-efficient by softening hard edges by thinning and pruning edges (to increase porosity above 30%, see Minvielle et al., 2003), by planting hedges along external plantation edges to control turbulence development (Morse et al., 2002), and by re-designing the shape of planting blocks during harvesting? This is amenable to investigation through simulation modeling (Krzikalla, 2005), and through experimental modification of existing plantation edges.

Conclusion

The concern about plantations and water use expressed in recent reviews appears to have been built on a number of assumptions that have not been fully tested. Many factors have the potential to affect plantation water use, and few of these alternatives have been examined in detail. Several of these factors are amenable to management control, and there is scope to design and manage forest plantations deliberately for water use efficiency.

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