FOREST MANAGEMENT EFFECTS ON INTERCEPTION, EVAPORATION, AND WATER YIELD

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ABSTRACT

Water balance data for New Zealand forests with rainfall ranging from 1300 mm/a to 2650 mm/a show that interception is a major component of the total evaporative loss. Interception losses increase with annual rainfall and duration of canopy wetness. In the wetter environments studied, interception losses are approximately double the losses in transpiration. High evaporation rates during rainfall of intercepted water are implied by the observed losses and these conform to theoretical expectations given that surface resistance reduces to zero or near-zero when the forest canopy is wet. Using New Zealand data, some preliminary estimates of likely water yield changes as a consequence of vegetation change are made for selected combinations of climate and land-use change.

INTRODUCTION

Forests have traditionally been regarded by both hydrologists and foresters as requiring or using more water than crops (wheat, corn, etc) or pasture (Baumgartner, 1967, 1970). Numerous studies of water yield in relation to land use have confirmed this general observation (Hibbert, 1967). It has also been traditional in both forestry and hydrology to regard transpiration as the larger component of the total evaporation from forests and to assign a less important role to the evaporative loss via interception (Baumgartner, 1967, 1970; Miller, 1976). In some instances, however, studies have shown little difference between the water requirements of forest and pasture (e.g. Gash and Stewart, 1977) and recent studies in Britain (Calder, 1976, 1978) and New Zealand (Rowe, 1976) have shown that in some climates interception losses can be double the water used by transpiration. These apparently conflicting observations can be reconciled by a consideration of the interaction between rainfall regime and the interception process, as has been shown by several recent studies in Britain and elsewhere (Stewart, 1977, 1979; Thom and Oliver, 1977; Singh and Szeicz, 1979). This paper briefly reviews these studies and outlines their importance for predicting water yield from forested areas in New Zealand. We also present water balance and interception data for some New Zealand forests that confirm the importance of rainfall interception in determining water yield from forested regions.

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Lastly we make tentative predictions of water yield changes likely to be caused by vegetation changes in specific regions, and suggest a strategy for prediction in regions where limited data are available.

RELATIVE IMPORTANCE OF TRANSPIRATION AND INTERCEPTION

Numerous overseas studies in the past decade and recent studies at Thetford Forest in Norfolk, UK, at Plynlimon in Wales, and in eastern Canada (Stewart, 1977; Calder, 1978; Singh and Szeicz, 1979) have revealed a number of factors which determine both the water use by forests and the relative importance of interception and transpiration.

Evaporation rates of water intercepted by a forest canopy are typically three to four times as great as day-time evaporation rates during transpiration when the canopy is dry; this is because of the low resistance to diffusion of water vapour from the wet, aerodynamically rough surface of a forest. Resistance to diffusion of water vapour from dry forest is dominated by the canopy or surface resistance (controlled by internal and stomatal resistances) which may be an order of magnitude greater than the aerodynamic resistance. When the canopy is fully wet, only aerodynamic resistance operates and the surface resistance reduces to zero. (A brief explanation of the theory underlying these findings is given in Appendix 1.)

Evaporation rates from intercepted water on wet pasture are approximately the same as day-time transpiration rates when the surface is dry. This results from the low surface resistance when the vegetation is dry (when soil moisture is not limiting), and the high aerodynamic resistance whether the pasture is wet or dry. Because of the low roughness of pasture, mixing of air passing above the vegetation is inefficient (high aerodynamic resistance), thus the removal of the surface resistance when the vegetation is wet has little effect on evaporation rates (Burgy and Pomeroy, 1958; McIlroy and Angus, 1964; McMillan and Burgy, 1960; Stewart, 1979).

Differences in temperature and humidity gradients above wet forest and wet pasture confirm the different rates of evaporation occurring from the two vegetative covers and show that large scale advection of energy from up wind must be present to maintain the high rates of evaporation from wet forest canopies (Stewart, 1977; Thom and Oliver, 1977; Pearce *et al.*, 1980).

The frequency and average duration of canopy wetness are important determinants of the relative importance of interception and transpiration in the total evaporation from forest cover. In areas with high rainfall and high numbers of rain days evaporation of intercepted water can be 70% of the total evaporation. Calder (1976, 1977) shows that at Plynlimon, with 2700 mm of rainfall, evaporation of intercepted water in a spruce forest accounted for 790 mm of the 1100 mm total evaporation. In contrast, at Thetford Forest with 600 mm rainfall, intercepted water in a Scots pine plantation accounted for 214 mm of the 566 mm total evaporation (Gash and Stewart, 1977). Here, because of the low frequency and short duration of canopy wetness, water use by the forest was found to be very similar to that by pasture.

Bowen ratio data summarised by Jarvis *et al.* (1976) suggest that transpiration losses for forests are very similar to those for short vegetation under well-watered conditions, although the Thetford studies (Stewart and Thom, 1973; Gash and Stewart, 1975, 1977) suggest lower transpiration totals for forest than for pasture.

Transpiration rates for various tree species used in plantation forestry in Britain show remarkably little variation with location and climate (J. M. Roberts, pers. comm.). These data suggest that, in temperate environments without seasonal soil moisture deficits, the range of annual transpiration losses among forest types is narrow. Differences in annual transpiration between different forest types at the same site are likely, therefore, to be small.

Studies of changes in water yield at Coweeta, North Carolina, in response to conversion from deciduous hardwoods to eastern white pine (Swank and Miner, 1968; Swank *et al.*, 1972; Swank and Douglass, 1974; Swift *et al.*, 1975) have shown that most of the change in water yield is accounted for by differences in interception losses.

If the general relationship between rainfall duration and totals and the relative importance of interception is found to be the same in New Zealand as in Britain, and if transpiration totals show the same consistency among sites and climates as found elsewhere, these results have considerable importance for a number of applied forest hydrology problems in New Zealand. Since the processes involved, especially those in evaporation of intercepted water, are fundamentally physical rather than biological, the results noted above are probably applicable in general terms to New Zealand forests.

WATER BALANCE AND INTERCEPTION DATA FOR NEW ZEALAND FORESTS

Until recently, few data on the water balance of New Zealand forest areas have been available. In the last decade, however, several catchment studies and a number of studies of components of the water balance have begun to remedy this lack.

Maimai experimental catchments, north Westland

Eight small catchments in beech-podocarp-hardwood forest in Tawhai State Forest near Reefton have been instrumented for a detailed study of hydrologic changes accompanying various forest management practices (Pearce *et al.*, 1976). Annual rainfall averages approximately 2650 mm and annual runoff from the undisturbed forest averages 1550 mm, thus total losses are 1100 mm. Interception studies (Rowe, 1976, 1979) reveal an average annual interception loss of c. 650 mm, thus transpiration and groundwater losses combined do not exceed 450 mm annually. The magnitude of groundwater loss is unknown and is probably spatially variable because the underlying compacted gravels vary in permeability. A first order estimate of 100 mm per year seems conservative but not unreasonable. Thus, to a first approximation, interception losses account for about two-thirds of the total evaporative loss. Despite differences in the distribution of rainfall and in rainfall intensities, the annual rainfall and number of raindays at Maimai are very similar to those at Plynlimon (Calder, 1976, 1978). The remarkable similarities in total evaporative losses and the proportion of evaporation accounted for by interception at the two sites confirm the importance of the frequency and duration of canopy wetness in apportioning evaporative losses between interception and transpiration at Maimai.

Big Bush catchments, south Nelson

Four experimental catchments in beech-podocarp-hardwood forest in Big Bush State Forest near Korere are also instrumented in a study of their hydrologic regime and changes resulting from species conversion and beech management. The catchments are described by O'Loughlin *et al.* (1978) and Pearce and McKerchar (1979). Annual rainfall here is approximately 1800 mm, with annual runoff approximately 900 mm. Evaporation of intercepted water accounts for about 400 mm of the 900 mm total loss. Again groundwater losses are unknown and probably are spatially variable but an upper limit of 100 mm/a is likely. This approximate water balance suggests a transpiration loss of the order of 400 mm/a. The apparent slight increase in transpiration relative to the Maimai area is in keeping with the climatic differences between the areas. Big Bush is slightly warmer, with longer periods of dry canopy, and although specific data are not available for Big Bush, annual radiation input and sunshine hours are probably larger at Big Bush than at Maimai. The reduced importance of interception in the Big Bush water balance is in keeping with the lower total rainfall and lower rainfall frequency than at Maimai. Nevertheless, interception losses account for approximately half the total evaporative losses.

Taita native forest catchments

A number of publications describe the water balance and interception data for the Soil Bureau's catchments at Taita (Jackson, 1972, 1973; Aldridge and Jackson, 1973; Jackson and Aldridge, 1973). Jackson's (1972 and 1973) analysis of radiation and water balance data clearly stated the differences between evaporation from wet and dry pasture and wet and dry forest in relation to differing surface and aerodynamic resistances, and concluded that large-scale advection of energy was necessary to sustain the evaporation of intercepted water at least during winter months. Evaporation rates from wet grass (intercepted water) and dry grass (transpiration) were within 10% of each other, but evaporation rates of intercepted water from the forest canopy were up to six times as great as transpiration rates. Interception loss from native forest catchment averaged 400 mm/a, and transpiration was between 430 and 630 mm/a, i.e. interception accounted for 40-50% of the evaporative loss. Annual evaporation from the forested catchments was approximately 170 mm more than *potential* evapotranspiration from grass (Jackson, 1972) but measured runoff averaged only 24 mm less than actual runoff from a pasture catchment in 1970-72 (Jackson, 1973). This result suggests advective enhancement of evaporation from grassland as well as forest.

The seasonal distribution of both rainfall and canopy wetness (more frequent and of greater duration in winter) indicates marked seasonal differences in relative water yield of grassed and forested areas. High intercepted water evaporation from forest in winter indicates less winter runoff than from grass, but in summer, transpiration rates from grass may be higher than from forest because of the lower canopy resistance (Jackson, 1972). Higher summer transpiration rates for grass would occur only when soil moisture was not limiting. Forest vegetation, with greater root penetration, is likely to be less affected by soil moisture limitation than is pasture cover. The expected seasonal contrasts between forest and grassland were confirmed, but with smaller differences than expected, by a comparison of runoff records from two monitored catchments (Jackson, 1973).

Moutere experimental studies

Three catchment experiments involving conversion of gorse scrub to radiata pine (2 catchments) and conversion of pasture to radiata pine have been described by Luckman and Duncan (1978).

Their data show that a marked increase in annual water yield occurred after clearing and burning of gorse. Yield was increased for about three years after a clearing which was followed immediately by planting, but increased yield persisted for at least five years after initial clearing where a second burning treatment was used and planting was delayed 18 months after the initial clearing. In both treatments, yields returned to, or slightly below, pre-treatment levels six years after planting of radiata pine (1500 stems/ha). In the years of greatest increase, annual yields were two to three times greater than pre-treatment levels.

Little change in annual yield occurred for four years after planting the pasture catchment. From the fourth year to the eighth year, a steady decline in annual yield occurred; after eight years annual yield was about one-third of pre-treatment levels. The reduction in yield was not seasonally uniform. Greatest absolute yield reductions occurred in the winter (July-Sept) quarter; 50% of the annual reduction occurred during these months. Percentage reductions in yield during summer and autumn were large, but *actual* reductions were typically < 10 mm per quarter. Absolute reductions for both quarterly and annual periods are closely linked to total rainfall, except for the autumn quarter.

As Luckman and Duncan (1978) suggest, the observed changes in yield appear closely linked to changes in the interception characteristics of the vegetative cover. Both the changes in annual yield, and the seasonal distribution of yield changes are in close conformity with Jackson's (1972, 1973) analysis of Taita data, and with British and North American data on the role of interception in water yield changes. The Moutere pasture to pine conversion caused large reductions in yield in winter and in the wet summer of 1975, but small *absolute* reductions in the summer and autumn quarters. The yield reduction in summer and autumn is during a period of soil moisture deficit which restricts transpiration from grass cover, but has less effect on transpiration from the more deeply-rooted young trees. The magnitude of the summer and autumn-quarter *percentage* yield reductions caused by conversion from pasture to forest at Moutere is unlikely to be repeated in regions with less severe soil moisture deficits in summer and autumn. The Moutere results are probably a good guide to the type of changes to be expected in other regions with large seasonal soil moisture deficits. Neither the absolute nor percentage reductions found at Moutere should be extrapolated to other regions without specific data to demonstrate similarity of rainfall distribution, permeability and moisture storage characteristics of the regolith, and seasonal distribution, duration and magnitude of soil moisture deficit.

ESTIMATING LAND MANAGEMENT-RELATED WATER YIELD CHANGES

The New Zealand water balance and interception data reviewed above strongly suggest that the relative roles of transpiration and interception in forest evaporation, and the relationship between rainfall climate and the components of total evaporation are in conformity with the measured and theoretical results discussed earlier and in Appendix 1. Using the data we have described, then, in that theoretical framework, we can make tentative predictions of water yield changes that are likely to result from some land use changes.

The basic requirements for predicting the effects on water yield of a land management change are an estimate of interception loss and an estimate of annual transpiration for both the existing vegetation and for the vegetation to be imposed on the area in question. The consequences of the vegetation change can then be assessed by comparing the total evaporation from both vegetation types, i.e.

$$E = I_g + T + E_s$$

where E = total evaporation
I_g = gross interception
T = actual transpiration
and E_s = evaporation from soil surface

For many vegetative covers, E_s is sufficiently small that it may be neglected, and changes in E_s between two different vegetations that completely cover the ground can probably be neglected. Where major changes in the amount of bare ground occur because of a land management change, changes in E_s must be taken into account. Where estimates of T are not available for each vegetation type, it may be satisfactory to assume that transpiration losses for different covers at the same site will not differ greatly. Evidence reviewed by Jarvis *et al.* (1976) indicates that forest vegetation has approximately the same ratio of evaporation to net radiation as short vegetation. Although net radiation for forests is larger than for pasture, canopy resistances are also larger for forests, thus differences in transpiration rate under the same conditions are likely to be small. The Thetford forest data suggest that conifers have lower transpiration rates than pasture, but the Thetford ratio of evaporation to net radiation is substantially smaller than those reported for other coniferous forests (NcNaughton and Black, 1973; Gay, 1972; Hicks *et al.* 1975; McCaughey, 1975; Tajchman *et al.*, 1979; Black, 1979). This likely similarity of transpiration rates and amounts for different vegetation types at the same sites underlies two important principles on which the predictions made in this paper are largely based:

1. If transpiration rates and annual amounts are similar for two different covers at the same site, then differences in total evaporation will be dominated by differences in interception losses.

2. Differences in interception losses can be estimated from the difference in gross interception, because the transpiration that would have occurred in wet periods if the canopy had remained dry will be very similar for both vegetation types.

In regions where data are available from gauged catchments and process studies, annual transpiration amounts for the existing vegetation can generally be obtained as a residual in the water balance, provided the gross interception loss is known. Appropriate interception loss data for the vegetation to be imposed on the area can often be obtained from studies in other regions of similar climate. Annual transpiration losses for the vegetation to be imposed can be obtained by extrapolation of data from other areas, from calculations using various evaporation models with suitable meteorological data, or by assuming little variation in transpiration rates and amounts between the original and imposed vegetation.

Some studies have reported different water yields from catchments with varying aspects that have undergone similar changes in vegetation. Hibbert (1967) notes major differences between north-facing and south-facing catchments in North Carolina, but similar results have not been obtained in other Appalachian catchment experiments. Differences in yield changes at Moutere (Luckman and Duncan, in prep.) may be partly attributed to aspect differences. Estimates made following the principles outlined above do not take into account aspect-related variations in water-yield response to vegetation change. The mechanism of such aspect-related variations is not well explained, nor do such variations fit easily into a general explanation of varying interception losses as the cause of varying water yields.

Conversion of indigenous mixed forests to radiata pine plantations, north Westland and south Nelson

Interception data for radiata pine at sites with rainfall of 1200-1500 mm/a reveal interception losses ranging from c. 20 to 30% of gross rainfall (Blake, 1975). These data are for stands with 1000-2000 stems/ha. The mixed forest of the Maimai region has an interception loss averaging 26% of gross rainfall; at Big Bush interception loss is about 21% of gross rainfall. Although data for pine stands in areas of similar rainfall regime are not available, it seems unlikely that major changes in interception losses will result from conversion to pine plantations especially in areas where trees are widely spaced (300-500 stems/ha).

Estimates of annual transpiration from radiata pine are difficult to obtain. Total loss data from water balance studies are of limited assistance since they contain an unknown component of interception loss. The studies reviewed earlier, however, indicate that differences in annual transpiration amounts for pine plantations and mixed evergreen indigenous forest are likely to be small.

A further constraint on likely changes in transpiration derives from the fact that transpiration is a semi-residual term in the water balance, i.e. both interception and storm runoff components (approx. 1700 mm at Maimai, approx. 700 mm at Big Bush) are satisfied first, then the remaining 900 mm (Maimai) or 1100 mm (Big Bush) of precipitation input are apportioned between delayed runoff, transpiration and groundwater discharge. On steep slopes with free-draining soils such as at Maimai and Big Bush, downslope drainage of soil moisture to supply delayed runoff will in effect compete with transpiration for the stored soil moisture. Delayed runoff accounts for about 550 mm at Maimai and 650 mm at Big Bush. Transpiration accounts for about 350 mm at Maimai and 400 mm at Big Bush. There is little reason to expect pine plantations to dramatically change the effectiveness of downslope drainage in either region.

The small magnitude of transpiration relative to interception in the undisturbed forest, the probable similar interception efficiencies of the two forest types, the lack of firm evidence to suggest that pines transpire more than the indigenous forest, and the limited residual rainfall input available to sustain any major increase in transpiration, combine to suggest that long-term changes in water yield resulting from conversion are likely to be small in north Westland. In south Nelson, if a major increase in transpiration occurred on conversion, long term yield changes, would probably be proportionally greater than in north Westland, because delayed runoff constitutes a larger percentage of the water balance. Some of the moisture stored in the soil which sustains delayed flow could be utilised in enhanced transpiration, *if that occurs* after conversion to radiata pine.

In the likely worst case in north Westland, allowing for c. 30% increase in transpiration (to 450 mm/a) and c. 15% increase in interception (to 800 mm/a), the long-term yield reduction would be c. 200 mm/a, or 13% of present yield. For south Nelson, allowing the same proportional increases in transpiration (to c. 530 mm/a) and interception (to c. 470 mm/a), the long term yield reduction would be c. 200 mm/a, or 22% of present yield. We believe, however, that changes of this magnitude are unlikely to occur. In both areas, interception loss may well decrease rather than increase, and only minor transpiration changes will occur, only minor (c. 50 mm/a) changes are likely to occur. Comparative interception studies are presently underway and should enable prediction of changes in interception loss in the near future.

Clearance of scrub or clearfelling of mature forest

Increases in water yield should follow the clearance of scrub or felling of forest. The increased yield will derive partly from decreased interception loss and partly from decreased transpiration. The magnitude of the increase in yield should be related to annual rainfall for areas where the pre-clearance vegetation is the same. Where burning follows clearing, the decreases in both interception and transpiration are likely to be greater than for unburned areas.

Clearing of gorse scrub at Moutere caused a doubling or trebling of water yield in the first and second years after clearance (i.e., 170 mm to 260 mm increase). Initial yield increases were larger, as expected, in the catchment that was burned twice and received more extensive clearance, but aspect differences between the two treated catchments may also be responsible for this difference. Interception data for gorse at Moutere (Blake, 1972; 1975) suggest annual interception losses of about 35-40% of gross rainfall (i.e., 400-450 mm/a). Interception on residual dead scrub, enhanced soil evaporation, transpiration from scrub regrowth, and both interception and transpiration by the pine seedlings on the early-planted area, are presumably responsible for the differences between the post-clearing increases and an estimated pre-clearing sum of 800 mm for interception and transpiration (P (observed) = 1100 mm, R (observed) = 100 mm, I (observed) = 400-450 mm, G (assumed) = 200 mm; T by difference) = 350-400 mm). The pre-clearing interception loss may, however, be a useful guide to an upper limit of early post-clearing yield increases.

Firm data on post-clearfelling increases in yield for New Zealand forests are not yet available. Interception losses will be substantially reduced, especially if slash-burning follows clearfelling, and transpiration will also be reduced, particularly if slash is burned before replanting. Yield increases can be expected to be smaller (for fixed annual rainfall) where natural regeneration follows clearfelling than where conversion or replanting requires slash-burning. Here also, pre-clearing interception losses may be a useful guide to the likely upper limit of early post-clearing yield increases. The processes involved in producing the yield increase are, of course, more complex than simply the removal of the intercepting canopy. Thus, for the Maimai region, first-year increases in yield may be as much as 700 mm, and for the Big Bush areas as much as 450 mm. Preliminary data from two catchments in the Maimai study indicate approximately 650 mm/a increase for a 100% clear-felled and burned catchment, and 540 mm/a increase where c. 75% of the catchment was felled and the slash burned. Data from an Oregon area with a similar rainfall regime to the Maimai area, reveal a 620 mm first-year increase in yield after clearfelling of Douglas fir (Harr, 1976).

Interception loss data for forest and scrub vegetation types in various parts of New Zealand are summarised by Blake (1975) and these may be useful for predicting changes in yield for areas with rainfall regimes similar to that of the area in which data were collected. Interception data, especially when expressed as a fraction of gross rainfall, should not be extrapolated to different rainfall regimes for predictive purposes and even the most approximate predictions (such as those given here) should be based on data from areas with similar rainfall regimes.

Afforestation of scrub or grassland

Long term yield changes after afforestation are likely to be related to annual rainfall. Yields will generally be reduced after afforestation. In broad terms, drier areas will undergo smaller changes in yield than wetter areas. Data from Thetford Forest in Britain suggest yield changes will be small in areas with < 700 mm annual rainfall provided major soil moisture deficits do not occur. The apparently low transpiration rates at Thetford may, however, limit the applicability of Thetford comparisons of water use. Afforestation of grassland will induce greater yield changes than conversion from scrub to forest. The relationship of yield change to annual rainfall is also affected by the seasonality of rainfall. Areas with a pronounced summer and autumn period of limited soil moisture are likely to exhibit greater proportional yield reductions than are areas with seasonally more uniform rainfall and soil moisture but similar annual rainfall. The greater yield reduction during soil moisture deficit periods occurs because the rooting depth of forest trees is greater than grass or scrub species, thus the forest can maintain higher transpiration rates during periods of soil moisture deficit. Absolute yield reductions will normally be greatest in wet seasons and wet years. The increased interception loss (based on data collected from areas with the same or a similar rainfall regime) will often be a good guide to the reduction in yield.

Estimation of yield change is more difficult where interception gains from fog also occur, e.g. eastern Otago tussock grasslands (Mark and Rowley, 1976; Mark and Holdsworth, 1979). Data for each vegetation types on interception losses during rainfall, interception gains from fog, and changes in snow interception and evaporation from snow for high altitude areas are required before reliable predictions of yield change can be made for these regions.

A stategy for predicting water yield changes in regions with limited data

In areas where water balance data from gauged catchments are not available, and process studies have not been carried out, estimates of transpiration and interception must be obtained from calculations and models based on the theory of evaporation. Model calculations will often require some input from short-term process studies. In order for such estimates to be useful, they must be obtainable from the types of data that are routinely collected at meteorological observation stations.

Interception loss estimates may be obtained from the analytical model of Gash (1979), which in its simplest form can be used with daily rainfall totals. Estimates of various stand parameters and $\bar{E}$, the mean evaporation rate from a saturated canopy, must be derived from a short-term study of interception losses in individual storms; these studies should ideally be carried out in the same or similar rainfall regime to the problem area, and in vegetation of appropriate density and structure. Gash's model assumes one storm per rainday, and effectively assumes a maximum storm length of 24 hr. If these assumptions are not met the model may give predictions that are seriously in error. Alterations to the model structure or empirical adjustments for the proportion of storms exceeding 24 hours duration may be possible, however, to suit local conditions. For many situations it should be possible to predict interception loss to within ±10% using Gash's model with daily rainfall data, and using stand parameters and the average saturated-canopy evaporation rate estimated from a short-term study of interception.

Thom and Oliver (1977) have recently derived a version of the Penman evaporation equation, suitable for use with daily data, which is a special case of the Penman-Monteith equation (with an explicit value for aerodynamic resistance). Tests of a version of the Penman-Monteith equation show good agreement of estimates using daily data with those using hourly data (J. H. C. Gash, pers. comm.), thus there is good prospect for estimating transpiration amounts using daily meteorological data, provided accurate values for surface and aerodynamic resistances are available. In both equations, transpiration estimates are relatively insensitive to the value of the aerodynamic resistance, thus using an aerodynamic resistance calculated from the wind profile (as though the site were uniform and flat) is unlikely to cause major errors. Estimating diurnal and seasonal variations of surface resistance is the main stumbling block to estimating transpiration. At present only one forested site in New Zealand (the Puruki subcatchment of Purukohukohu experimental catchment) is sufficiently well instrumented to enable calculations of surface resistance from above-canopy micrometeorological data. Surface resistance data for other pine species, and other conifers, are available from U.K. data (Gash and Stewart, 1977; Calder, 1977). Comparison of radiata pine surface resistance data from Puruki with these overseas data would be an important step in determining to what degree the simple surface resistance models used by Gash and Stewart and by Calder are applicable to radiata pine in New Zealand conditions.

For short vegetation that is not under water stress and where advective enhancement is not great, McNaughton *et al.* (1979) have recommended that Priestly and Taylor's method be used in preference to the Penman method. Priestly and Taylor's method requires net radiation measurements; where these are lacking, they can be estimated from one of a number of empirical relationships between sunshine hours and net radiation, using a suitable value for the albedo of the particular crop.

A suitable method for the prediction of water use by both pre-change and post-change vegetation, given current techniques and available data, would appear to be:

1. estimate interception loss for tall vegetation using the analytical model of Gash (1979); and
2. estimate transpiration for forests or short crops using Thom and Oliver's equation or a daily version of Penman-Monteith equation. An alternative for short crops is Priestly and Taylor's equation.

CONCLUSION

The water yield of forested areas is heavily dependent on the interception characteristics of the vegetation, and on the frequency and duration of canopy wetness. In areas of high rainfall, interception can account for 60-70% of the total evaporative loss. In areas with more than about 1500 mm/a rainfall, water yield changes following vegetation manipulation are likely to be dominated by changes in interception loss. In areas with rainfall of less than 700-800 mm/a, changes in yield are likely to be small unless marked seasonal soil moisture deficits occur. In areas with moderate rainfall, water yield changes can probably be predicted from studies of interception loss in both the appropriate vegetation types. Where major seasonal soil moisture deficits occur, the ability of different vegetation types to exploit deep soil moisture stores to maintain transpiration must be taken into account in assessing likely yield changes.

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APPENDIX—Evaporation from vegetated surfaces.

A comprehensive yet simple theoretical description of the evaporation from a vegetated surface is the Penman-Monteith equation (Monteith, 1965). The evaporative surface of the vegetation is assumed to be represented by a single layer of "canopy", whose surface area is equal to the summed area of all individual leaves. The energy flux in evaporation (λE) is given by:

$$\lambda E = \frac{\Delta R_n + \rho c_p\,(VPD)/r_a}{\Delta + \gamma(1 + r_s/r_a)} \qquad (1)$$

where λ = latent heat of vaporisation (J/kg)

Δ = slope of saturation vapour pressure curve (mbar/°K)

ρ = air density (kg/m^3)

c_p = specific heat of air at constant pressure (J/kg/°K)

γ = psychrometric constant (mbar/°K)

R_n = net radiation (W/m^2)

VPD = vapour pressure deficit (mbar)

r_s = diffusive resistance to passage of water vapour from inside leaf to leaf surface or "bulk surface resistance" (sec/m) (approx. equivalent to $\frac{\text{stomatal resistance}}{\text{leaf area}}$)

r_a = diffusive resistance to passage of water vapour from leaf surface to reference level in atmosphere (sec/m)

E = evaporation rate (kg/m^2/sec = mm/sec)

Equation (1) applies to both wet and dry canopy surfaces, i.e. to both interception and transpiration. When the canopy is fully wet, there is effectively no resistance to transfer of water vapour from inside the leaf to the leaf surface, i.e., $r_s = 0$. Equation (1) then simplifies to:

$$\lambda E = \frac{\Delta R_n + \rho c_p\,(VPD)/r_a}{\Delta + \gamma}$$

or

$$E = \frac{\Delta R_n + \rho c_p\,(VPD)/r_a}{\lambda\,(\Delta + \gamma)} \qquad (2)$$

For different vegetative covers experiencing the same meteorological conditions, Δ, ρ, c_p, λ and γ are effectively constant, so evaporation from different *wet* vegetative covers at the same site depends on R_n, VPD, and r_a. Differences in R_n will occur among vegetative covers because of different albedo values, but these differences will be rather small, and R_n values are in any case small during rainfall. As least initially, differences in VPD above the two covers will be small, but will become larger with time if different evaporation rates occur. To a first approximation, then, evaporation rates from different *wet* vegetative covers will depend inversely on the magnitude of their aerodynamic resistances (r_a).

Aerodynamic resistance is inversely related to the roughness length of the surface cover, i.e. to the length or height of projections from the surface. Some approximate values for different surfaces at a wind speed of 2.5 m/sec measured at 10 m above the surface are:

	Open Water	Grass	Field Crop	Forest
Roughness length (m)	0.001	0.01	0.1	1.0
Aerodynamic resistance (sec/m)	200	115	50	12

Thus in wet canopy conditions forests will evaporate intercepted water much faster than short crops or grass because of the low aerodynamic resistance of the forest.

Under dry canopy conditions, aerodynamic resistances remain in the relative order shown above, but surface resistances are partly related to crop height.

	Open Water	Grass	Field Crop	Forest
Surface resistance (sec/m)	0	40	60	60–120 (approx)
r_s/r_a	0	0.3	1.2	5– 10

Because r_s/r_a is larger for forest cover, and because r_s/r_a appears in the denominator of Equation (1), evaporation rates from a dry forest canopy may be lower than for grass or short crops, except when soil moisture deficits limit the evaporation rate from the shallower-rooted grass or crops. Higher net radiation for forests because of lower albedo will, however, offset the effect of the large r_s/r_a to some extent. A number of experimental studies indicate that differences in transpiration between forests and short vegetation are likely to be small.

The above considerations indicate that the relative importance of transpiration and interception for forest, and the effect of tall vegetation on water yield, will be closely related to the duration and frequency of canopy wetness. Changes in water yield caused by manipulation of vegetation cover will be principally related to changes in interception characteristics. The important exception is where major seasonal soil moisture deficits occur, since trees can exploit a greater rooting volume than short vegetation, and can thus continue transpiration when grass or field crops have effectively ceased to transpire.