

# Measuring interception loss and canopy storage in dryland vegetation: a brief review and evaluation of available research strategies

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## Abstract:

The interception storage capacity has been measured for a range of dryland plants. Interception losses over time, however, arise in rain events that deliver either less or more than the canopy capacity. The fate of water in these cases depends on the efficiency with which the intercepted water is returned to the atmosphere by evaporation from the plant canopies. Two primary methods to estimate interception losses are (i) calibrated process-based models of interception and evaporative loss and (ii) direct measurement. Models have been applied only rarely to dryland plant communities, and direct measurement techniques are in need of additional testing and refinement. Most published estimates of interception loss in dryland plant communities therefore appear to be based upon inadequate data and methods. Research needs in this area are highlighted. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS canopy interception; dryland shrubs; throughfall; stemflow; evaporation

## INTRODUCTION

Canopy interception losses of precipitation affect the amount of water reaching the soil in several ways, and are therefore of relevance to many hydrological investigations. In rain events that fail to fill the canopy store, much of the water received may be held on the leaves and later returned to the atmosphere by evaporation. When canopy storage capacity is exceeded, however, some water can be funnelled as stemflow and delivered more efficiently to the soil around the root zone than had the interception not occurred (e.g. Glover *et al.*, 1962; Glover and Gwynne, 1962; Pressland, 1973; Mauchamp and Janeau, 1993), and this increases the efficiency of water use from light rainfalls.

Interception losses have been widely measured in forests, particularly in relation to evaluating the environmental effects of logging (e.g. Dykes, 1997; Asdak *et al.*, 1998a, b). Interception measurements have been attempted less often in the tree, shrub and grass communities of drylands. Interception losses from forests are greater in absolute volume than those from dryland communities, because of the more extensive plant canopy and the higher frequency of rain events. A recent estimate (Dunkerley and Booth, 1999), however, suggested that a grass community in arid western New South Wales, Australia, forfeits 30% of the annual rainfall to interception, a *proportion* as large as that of many forests (Rutter *et al.*, 1971). This significant annual loss results from the many small rain-day rainfalls, which are largely intercepted and returned to the atmosphere by evaporation. A similar estimate (27.2% loss) was reported for a semi-arid Mexican shrubland (Návar and Bryan, 1990), but much lower values have also been found. For shrublands

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in Utah, West and Gifford (1976) estimated interception losses of about 4% of annual rainfall. In a multi-year study of a semi-arid Australian mallee woodland, where the tree canopy cover was 21%, Nulsen *et al.* (1986) showed that interception losses averaged only 3% of annual rainfall.

Clearly, interception losses are geographically variable and must be quantified in studies of dryland hydrology. As is the case for forest-based studies, however, no standard field methods have become established. Some are best suited to the estimation of long-term (e.g. seasonal or annual) losses, whereas others can provide data from single rain events, and can be used to determine the storage capacity of an individual plant canopy. The objective of this note is to draw attention to the diversity of measurement techniques, to highlight potential difficulties with some, and to offer recommendations for additional research needs in the area of dryland canopy interception.

### THE TERMINOLOGY OF CANOPY INTERCEPTION

No universally accepted system of terminology has emerged in studies of plant canopy interception. It is agreed generally that interception on a single plant may be described in terms of the *canopy storage*,  $C$ , i.e. the volume of water that can be held. In some models, and under some field conditions, the amount of water held can temporarily exceed  $C$ . This can occur when there is water in transit across leaves and stems, and which would drain from the plant over a short time once rain had ceased. Therefore, it is necessary to define a *static canopy storage* as that volume of water that can be retained on the canopy and that will not drain from it to the ground. Indeed, Grah and Wilson (1944) recognized three components to canopy storage, which they termed *transitory storage* (water that would later drip off), *conditional storage* (water that could be dislodged by wind vibration of the plant) and *residual storage* (water that can only be removed by evaporation). In most studies designed to estimate  $C$ , wind is explicitly excluded, so that the sum of conditional and residual (static) storages is measured.

Water drops that pass through the canopy to reach the ground collectively form the *throughfall*. Some above-canopy rainfall reaches the ground directly through gaps in the canopy, without striking the plant. This component of throughfall is termed *free throughfall*,  $T_f$ . The balance of throughfall is water that is released from leaves and branches, with a drop-size distribution that therefore may be different to that of the above-canopy rainfall. The name *released throughfall*,  $T_r$ , is suggested for this component. Water also may be delivered to the ground via the stemflow pathway, along which some stem and bark storage may occur. As was emphasized by Specht (1957), stemflow does not always occur in the direction of the main stem, but may, depending upon plant form, travel down branches to deliver water in drip form from the edges of the canopy.

Some rain events fail to deliver sufficient water to satisfy  $C$ , whereas others greatly exceed this amount. Furthermore, some intercepted water is lost to evaporation during rain as well as during breaks within it, and the amount lost depends upon meteorological conditions, including temperature, humidity and wind speed. The volume of water lost by evaporation from the wetted canopy during some period of time is the *canopy interception loss*,  $I$ . As  $I$  depends on the meteorological conditions, the amount of water returned to the atmosphere from a wetted canopy varies greatly between events. In other words, values of  $I$  are highly variable on an event basis, and can be more or less than  $C$ . The tallying of interception losses, perhaps through the course of a season or a year, enables the overall consequences of interception loss for the surface water balance of the plant community to be estimated.

Thus, there are two different data requirements for studies of the role of interception in drylands: (i) a knowledge of the canopy storage volume,  $C$ , and its variation among plant species. This parameter indicates the threshold storm size likely to result in significant overflow of water through the canopy and so downward to the soil surface. (ii) Estimates of the longer term canopy interception losses,  $I$ , arising when water intercepted is returned to the atmosphere via evaporation. This depends on the value of  $C$  for the plants concerned, and on the number and sizes of rain events that deliver water in amounts that exceed or that fail to reach  $C$ . Both kinds of data are commonly obtained through the study of individual plants, and aggregated for whole plant communities through the use of other data (such as the density with which the

plants grow in the landscape). As will be shown later, knowing the values of  $C$  does not permit the straightforward estimation of time-integrated values for  $I$ , which would depend upon the availability of meteorological and other data, and a model in which to process these (e.g. Rutter *et al.*, 1971; Massman, 1980; Liu, 1997). Therefore, field methods to measure daily, weekly or longer term values for  $I$ , some of which are discussed below, are of potentially great utility.

### THE FIELD MEASUREMENT OF $C$ AND $I$

In studies of dryland plants and plant communities,  $C$  has most often been determined by direct experiment on individual plant specimens. In contrast, although it is possible to measure directly,  $I$  has principally been estimated by using direct measurements of  $C$  for individual plants and up-scaling of these data to the level of a plant community by employing estimates of the area-wide canopy cover from line-intercept transects (e.g. West and Gifford, 1976).

The up-scaling procedure commonly adopted works as follows. Knowing the value for  $C$  for a particular species, together with the areal canopy cover within the plant community that is provided by that species, enables the aggregate volume that would be held by the community to be estimated for rain events delivering enough water to satisfy  $C$ . For example, the shrub interception studies in Utah performed by West and Gifford (1976) showed  $C$  to be 1.5 mm. West and Gifford used 200-m line-intersect transects to estimate that there was a 19.1% canopy cover of big sagebrush. From 20 years of rainfall records, they showed that there were on average 21 rain events supplying  $> 1.5$  mm between 1 April and 30 November (the rain season) each year. Thus, ignoring smaller storms, cumulative  $I$  for the rainy season was estimated as  $(21 \times 1.5 \times 0.191)$  or about 6 mm. This represented a loss to interception of 4% of the seasonal rainfall.

The up-scaling of values for  $C$  derived from test specimens in order to estimate values of  $I$  for the wider plant community as a whole in the way just illustrated has been widely adopted in dryland studies (Table I).

Table I. Details of selected published studies of canopy interception in dryland plants: procedures used to estimate  $C$  and/or  $I$  are noted in the right-hand column

Reference	Location and vegetation of study site	Canopy interception assessments ( $C$ or $I$ ) and methods used
Pressland (1973)	Charellville, Queensland, Australia: mulga woodland ( <i>Acacia aneura</i> )	$I$ from separate measurement of throughfall with subcanopy gauges and stemflow with tree collars
West and Gifford (1976)	Utah: arid shrubland of big sagebrush and shadscale	$C$ from weight gain of severed specimens under artificial rain; up-scaled to community $I$ using cover fraction data
Thurow <i>et al.</i> (1987)	Texas: two grass species and oak mottes	$C$ from weight gain of specimens under artificial rain; up-scaled to community $I$ using cover fraction data
Tromble (1988)	New Mexico: creosotebush and tarbush shrubs	$C$ from weight gain of specimens under artificial rain; up-scaled to community $I$ using cover fraction data
Návar and Bryan (1990)	Mexico: three shrub species	Separate measurement of throughfall with subcanopy gauges and stemflow with tree collars. Estimate of both $C$ and $I$ values for individual plants only
Wood <i>et al.</i> (1998)	Chihuahuan Desert, USA: 10 plant species	$C$ data from weight gain following submergence in water tank
Serrato and Diaz (1998)	El Ardal, south-east Spain: three shrub species	$I$ from 3 years of data collected with subcanopy tray
Dunkerley and Booth (1999)	Western New South Wales, Australia: two shrub species and one grass	$C$ from weight gain of specimens under artificial rain; up-scaled to community $I$ using cover fraction data

However, it is not a straightforward process. The value of  $C$  has, in all cases known, been estimated in calm air, and thus represents the sum of conditional and residual storage capacities, whereas in the field, vibration caused by wind may reduce the effective storage capacity to the lower, residual value. Further, under field conditions, storms may deliver too little rain to satisfy  $C$ , or evaporation proceeding simultaneously with light rain may result in losses greater than  $C$ , and this brings any reliance on estimates of  $C$  into doubt. More importantly, the procedure for estimating values of  $I$  applicable to a whole plant community involves a number of questionable assumptions. Key among these is the assumption that in storms delivering rain depths  $\geq C$ , plant canopies intercept this depth of water and no more. This ignores evaporation taking place during rain or in short breaks within the event, both of which can increase actual values of  $I$ . Given the atmospheric conditions of drylands, which often involve low atmospheric humidity levels combined with abundant solar radiation, it seems undesirable to ignore the evaporative contribution to  $I$ , which is routinely incorporated in canopy interception models for forests in humid areas. For example, the model of Liu (1997) correctly recognizes that interception loss is the total of canopy storage plus evaporation during rainfall. The mechanisms controlling evaporation and its role in canopy interception also have been explored by Stewart (1977), Gash *et al.* (1980, 1995), and Watanabe and Mizutani (1996). If there are significant evaporative losses, estimates of  $I$  that neglect these will be underestimates. Furthermore, evaporation rates during breaks in rain, or during the intervals between storms, must be allowed for because it is the rate of evaporation then that determines what fraction of  $C$  will be available for refilling when rain begins again.

An additional minor difficulty with the up-scaling procedure is that, in the event of oblique rain, the vertical canopy cover may not provide a suitable measure of the canopy area actually active in the interception of raindrops.

Finally, studies of forest canopy interception have highlighted the critical role of the boundary layer conductance, which measures the efficiency of water vapour transfer from the wet vegetation into the freely mixed atmosphere above. The closeness of tree spacing has been shown to influence this parameter strongly, so that more closely spaced trees lose less water to interception than identical trees more widely spaced. For example, in Sitka spruce at tree spacings of 2, 4, 6 and 8 m, interception loss volumes *per tree* at 2 m spacing were < 17% of the loss at 8 m (Teklehaimanot *et al.*, 1991). Particularly in dryland plant communities where the plant cover is patchily distributed, and more so where it is banded or otherwise patterned, effects like this may be quite marked, so that plants on the margins of a cluster must lose greater amounts to interception than plants within a cluster. Therefore, it remains to be shown that interception data on individual test plants (such as estimates of  $C$ ) can validly be transformed to community values simply by knowing the vegetation cover percentage. Instead, the structural arrangement of the plants in many cases seems likely to be an important determinant of interception losses.

An example of the contribution to  $I$  of evaporation under various conditions of canopy wetness can be obtained from the tropical rainforest study of Hutjes *et al.* (1990). Data disaggregated using the Gash interception model suggested that up to 7% of interception loss occurred from storms too small to satisfy  $C$ , 1% during wetting-up, 27% under conditions when the canopy was saturated, and 65% during drying out from large storms. Thus, the up-scaling procedure that has been widely used in drylands would result in an underestimate of at least 35% for this case, and, given the different storm and humidity characteristics of drylands, might ordinarily be significantly worse than this.

In essence, therefore, the widely adopted up-scaling procedure really only yields what may be termed plant-community values for  $C$ . To the writer's knowledge no dryland studies have adopted more comprehensive means of estimating  $I$  and evaluated the degree to which community-level estimates of  $C$  correspond with these. Indeed, the recent work of Domingo *et al.* (1998) on canopy interception in shrubs and grasses at a semi-arid Spanish site appears to be the only dryland study to have adopted a form of canopy loss model (the Rutter model) and validated it against observations made with stemflow collars and throughfall gauges.

The careful use of a field method to measure  $I$  on an event-basis (some of which are discussed below) would enable evaporative losses to be estimated in events that delivered a rainfall  $> C$ . This is because any

event interception losses greater than  $C$  that are not artefacts of the recording procedure must represent evaporative fluxes from the wet canopy. However, for rainfall totals  $< C$  this method will not work, because there is no way to apportion losses between progressive filling of the canopy store and evaporation. There remains a real need for an evaluation of the control that evaporation rates play in determining interception losses in dryland plant communities, especially for small events.

#### Measurement of $C$

The canopy storage  $C$  has often been estimated by using measurements of the weight gained by a specimen canopy that is exposed to simulated rain. Test plants are severed from the ground, and either mounted where their weight can be recorded continuously as they are wetted (e.g. Aston, 1979) or the weight gain is noted after sufficient rain has been applied to generate considerable released throughfall, at which point it is inferred that  $C$  has been satisfied (e.g. West and Gifford, 1976; Tromble, 1983). Weight may be checked at intervals to ensure that it is no longer increasing. In a variant of this method, Thurow *et al.* (1987) froze test specimens once  $C$  had been satisfied, and after weighing and subsequently oven drying and reweighing, determined the volume of water that was held. Recently, Wood *et al.* (1998) estimated  $C$  for some Chihuahuan Desert plants from weight gain of specimens wetted by immersion in a large tank of water. From weight gain data, it has been shown that  $C$  varies significantly among dryland taxa (e.g. Dunkerley and Booth, 1999).

#### Measurement of $I$

The value of  $I$  has been measured only infrequently. To do this, it is necessary to measure the *actual* static interception amount over some integration period. This has been done primarily by measuring  $P$ , the above-canopy rainfall, the below-canopy throughfall,  $T$ , and the stemflow,  $S$ , and estimating  $I$  from

$$I = P - T - S \quad (1)$$

Which is the same as

$$I = P - T_f - T_r - S \quad (2)$$

In other words, all water arriving at the soil surface beneath the plant is subtracted from the rain arriving over the same area above the plant. The difference provides the estimate of  $I$  for the integration period (storm event, day, week, etc.).

Given that rainfall,  $P$ , can be reliably recorded by a gauge located adjacent to a test plant, and that there is no variation of rainfall between the gauge location and the plant, this procedure hinges on the measurement of all water arriving at the soil under the plant canopy ( $T_f + T_r + S$ ).

### METHODS FOR MEASURING WATER DELIVERY UNDER PLANT CANOPIES

Measurements must be made of stemflow and throughfall for only that area lying under the plant canopy. Here a first procedural difficulty is encountered, that of defining the edges of the plant canopy. This has been done from an overhead image of the plant, on which a smoothed canopy border, bridging any gaps, is plotted. Alternatively, two orthogonal diameters may be measured, and the area of an ellipse defined by them taken as the canopy area of the shrub (e.g. West and Gifford, 1976). This smoothing or approximation procedure is termed canopy definition A, and only seems appropriate for plants with no or few gaps within the canopy. No objective rules appear to have been developed by which to distinguish a gap or embayment in a canopy from a location where the canopy merely extends outward from the stem on one radial axis less far than it does on adjacent axes. An alternative canopy definition (B), is to measure on an image the total area actually occupied by the irregular plant canopy, so ignoring any marginal gaps or enclosed gaps lying within

the borders of the canopy. Serrato and Diaz (1998) did this for dryland shrubs using image processing methods.

In the process of field measurement, both definitions have been adopted, although the second definition is perhaps the easier to implement in an objective fashion.

#### *The use of separate throughfall gauges and stemflow collars*

Throughfall can be estimated by placing collecting containers beneath the test canopy. For example, Návar and Bryan (1990) used six collectors, two near the shrub stem, two near the outer margins of the canopy, and two at intermediate locations. Domingo *et al.* (1998) used three to eight funnel collectors under test shrubs. This is akin to the practice common in forests, where large throughfall collecting troughs are used (e.g. Rutter *et al.*, 1971), although these are conventionally relocated at intervals to provide a larger sample of throughfall measurement sites. Similarly, in his studies of interception in Australian mulga trees, Pressland (1973) used multiple throughfall gauges located under each test tree. Stemflow must then be collected and tallied separately, using a collar wrapped around the stem to direct all flow to a collector (e.g. see Pressland, 1973; Návar and Bryan, 1990).

#### *The collecting tray technique*

As an alternative to the use of separate stemflow and throughfall collectors, all throughfall water arriving beneath the canopy may be conducted to a single container where its volume is recorded. A tray or other impermeable collecting surface is placed underneath the canopy, and the total volume collected during an integration period is subtracted from the above-canopy rainfall in order to estimate the interception loss in accordance with Equation (1). An important advantage of this approach is that it measures throughfall more thoroughly, which can show marked variability around a plant. On the other hand, no separate data on stemflow are provided.

Implementations of this method, with some variations, have been reported by Merriam (1961), Crouse *et al.* (1966) and Serrato and Diaz (1998). Crouse *et al.* (1966) sealed a circular area surrounding test grass plants by applying a coating of latex emulsion to the soil surface, and directing all arriving water to an adjacent measuring system. Interception was then expressed in terms of the canopy cover fraction within the borders of the sealed collecting surface, as measured with a point-counting frame.

A modification of this procedure was outlined more recently by Serrato and Diaz (1998), and used with dryland shrubs. In this approach, a square metal tray at ground level, with the stem passing through a central hole, replaced the latex seal of Crouse *et al.* (1966). Throughfall landing on the tray, and stemflow directed through the central hole, are directed to separate storage vessels and tallied. Also, in the modification of Serrato and Diaz (1998), the tray extended beyond the bounds of the canopy. The fraction of the collecting surface directly exposed to rain was measured in a vertical view, and water delivered to this area subtracted from the collected volume. Thus, canopy definition B described earlier was used. In this way, it was suggested, only stemflow and throughfall arriving at the area directly under the canopy were summed. As this method has been recently recommended, and offers the prospect of direct measurement of  $I$  over appropriate integration periods, particular attention is paid to it in the following discussion.

### POTENTIAL DIFFICULTIES IN IMPLEMENTING THE TRAY METHOD FOR RECORDING $I$

#### *The correction for rain caught on exposed parts of the collecting tray*

This correction is based on two key presumptions. The first presumption is that all rain arrives vertically. This follows from the fact that the area of exposed collecting tray within the plot but beyond the plant canopy is assessed from directly overhead. If rain arrives on a slanting trajectory because of wind, this presumption is no longer valid, and a larger area may be available for interception and evaporative losses. The second presumption is that all parts of the plant canopy behave rigidly and do not sag beneath the burden of intercepted water. If sagging did occur, this would alter the measured projected canopy area.

Indeed, sagging of grass interfered with the interception loss measurements of Crouse *et al.* (1966), who recommended that larger test plots be used to minimize the effects of this. Woody dryland shrubs seem unlikely to exhibit marked sagging, but this requires checking.

#### *Effect of the device upon the test plant*

As impermeable collectors trap the entire volume of stemflow and throughfall, they seem likely to significantly deprive the test plant of its primary moisture source. Although they reported data on individual plants spanning several years, Serrato and Diaz (1998) did not provide any evaluation of the potential effects of the measuring devices upon the test plants. The collecting box at ground level covers an area of up to 1 m<sup>2</sup>, by design extending beyond the limits of the plant canopy on all sides. Many dryland shrubs have root systems that are most abundant in the volume of soil below the above-ground parts of the plant. The collecting box would thus deprive the root system of all of the water that would normally infiltrate from below the canopy. This seems potentially a very severe impact, as the soils beneath many dryland shrubs are more porous and conduct water more readily than soils beyond the plant, and the zone around the stem is a vital point of entry for water. Given the long-term loss of these water sources (i.e. over several years in the trials of Serrato and Diaz, 1998), a deleterious effect on the vigour and dimensions of the plant canopy might be anticipated. If this is so, the interception properties would also be altered, detracting from the usefulness of the time-integrated  $I$  data collected. Suitable canopy measurement could be made at intervals to check for any effect of the installed device. Indeed, such regular canopy cover data were collected by Crouse *et al.* (1966) in their earlier work on grasses using their variant of this method, owing to the rapidity with which the canopy dimensions could change in response to rain. Crouse *et al.* (1966) noted no detrimental effect of surface sealing on grass growth, but their study location was relatively moist, with a mean annual rainfall of 678 mm. Arid and semi-arid locations, where the unavailability of soil moisture may limit plant growth, might be associated with greater stresses on the test plants. Furthermore, the circular collars used by Crouse *et al.* (1966) were only 25 cm in diameter (and those of Merriam, 1961, only 20 cm in diameter), whereas Serrato and Diaz (1998) used plots up to 1 m in width.

#### *Limitation on possible analysis of data derived from collecting trays*

During rain, the collecting box (parts of which are inevitably exposed to direct rainfall, either parts lying beyond the plant canopy or below gaps within it) will generally speaking shed water into the collecting reservoir. An exception arises for very small rain amounts, in which water landing on the box might be held by surface tension and remain undetected. Using a latex sealant, great care would be required to ensure that there were no low points in the surface in which water could pond. Assuming proper free drainage of the collecting surface, the amount of water being discharged to the collecting vessel would increase once the plant canopy was fully wetted up ( $C$  storage filled). This point, however, could not readily be detected using the devices like that of Serrato and Diaz (1998), because there would only be a gradual (and very slight) change in flow rate, and this might in any case be overshadowed by fluctuations in rainfall intensity. Therefore, the device, and the relation set out earlier, can be used only to determine the aggregate interception loss  $I$  over a period of time, and not the rain amount that fully satisfied the canopy storage  $C$ . Results in this form are of considerable value. The resulting data, however, depend very much upon the number and sizes of rain events at the study site (small rain depths yielding a high percentage loss to interception) and this cannot easily be overcome to isolate the role played by properties of the plant canopy itself. Therefore, collecting trays seem best suited to the estimation of  $I$  over suitable integration periods, on the condition that their use does not cause changes in the plant canopy being monitored, or on other relevant variables, such as the temperature of the soil below. Therefore, in order to pursue the issue of whether  $C$  data can be up-scaled to community values of  $I$ , the use of the collecting tray method would have to be supplemented by one of the available methods for the determination of  $C$ .

If this presumption about the mode of operation of the device is correct, then systematic losses within the device become potentially more significant. For example, temporarily detained water from small showers

might be held on the surfaces of the collecting box, and not recorded. This would result in overestimates of the losses to interception. Indeed, this 'box interception loss' is quite problematic. Although Serrato and Diaz (1998) briefly describe how they attempted to calibrate this effect (and so allow for it), the procedure appears inadequate. Box losses would arise for both direct rainfall on exposed parts of the box ( $Tl$  in the authors' symbolism) and for temporarily intercepted water falling from the canopy ( $Dr$ ). Thus, during data reduction, the recorded volumes of flow would need to be increased to compensate for the box losses. Presumably (Serrato and Diaz, 1998, do not explain this) the correction is applied in a procedure that is weighted according to the fractions of the box exposed to rain or lying beneath the canopy. No single correction factor can do this adequately, however. Consider a small rain event. Some water would land on exposed parts of the box and some would be held there, so that  $Tl$  would be underestimated. Thus, the measured water volume would have to be corrected. Beneath the canopy, though, no water might be delivered to the box, all of it being held intercepted on the plant. In contrast, a rain event sufficiently large to wet up all of the box would suffer losses in both  $Tl$  and  $Dr$ , but the error could be different in  $Tl$  (a small error perhaps) but larger in  $Dr$ . If only a little  $Dr$  is delivered to the box, the proportional error in this could be quite high. In other words, a single correction factor as adopted by Serrato and Diaz (1998) cannot in principle apply perfectly to all rain events. It is difficult to evaluate the procedure actually used by the authors in developing the data they have published, as it was not set out in the paper. The important point is that if data from many storms are aggregated, then the errors arising from incomplete correction of 'box losses' accumulate steadily. This potential source of error needs to be evaluated in interpreting values of  $I$  derived with throughfall collecting trays.

#### *Hardware problems with interception trays*

Water lost from collecting trays by outward splash appears to be a potential difficulty with this class of methods. For example, the flow collection box of Serrato and Diaz (1998) was equipped with only low walls inadequate to prevent outward splash losses. Such losses seem especially likely around the periphery, as water splashed here can readily cross the boundary of the box, and is at the same time most likely to be exposed to the intense drop impact from direct rainfall, because the edges of the box lie beyond the shelter of the plant canopy. Over the extended periods of time involved with the use of such devices to quantify  $I$ , accumulated splash losses might become a serious source of error. Serrato and Diaz (1998) did not comment upon the issue of splash loss.

## DISCUSSION AND CONCLUSIONS

The measurement of  $C$  by the observation of weight gain has been successfully adopted for use with dryland plants, and has been used to reveal how this canopy storage parameter varies among some taxa. Additional methods that have been developed for application in forest studies remain to be applied to dryland plants. These include the strain-gauge measurement of cantilever flexing of branches under the load of intercepted water (Hancock and Crowther, 1979) and the attenuation of a microwave signal by water held on plant canopies lying in its path (e.g. Bouten *et al.*, 1991, 1996; Wigneron *et al.*, 1996).

Measurement of throughfall using multiple gauges located under the canopy, together with separate measurements of stemflow, has been used successfully to estimate  $I$ . For many dryland grasses, however, and even for small woody shrubs, this procedure would be difficult to apply owing to the problems attending the collection of stemflow under these conditions. Additionally, the efficiency of small gauges in sampling spatially variable throughfall beneath dryland plants has not been demonstrated. It has been reported from forest studies that some throughfall gauges catch more than the above-canopy rainfall, rather than less as might be expected. This has been attributed to location of the gauge below a favoured drip-point on a branch above (Hutjes *et al.*, 1990). Throughfall exceeding rainfall is problematic in data reduction because it can result in negative values for  $I$ .

Using some form of collecting tray to quantify water arriving at the soil surface under a canopy, and so estimate  $I$  using Equations (1) or (2) above, has been less widely attempted, but in principle provides a more soundly based estimate of throughfall, and hence of  $I$ . This is because the small area receiving throughfall is not sampled, but rather the whole of the throughfall is gauged. This approach is attended by a number of potential difficulties, however, including detrimental effects on the vigour of the test plant and so on the characteristics of its canopy. This difficulty seems likely to be increasingly damaging for longer term observations, which are necessary in order to yield reliable values for  $I$ . The interception measuring device described by Serrato and Diaz (1998) appears to offer some attractive features. To judge from the published account of this device, however, its strengths and weaknesses were not fully analysed by the authors, and remain in need of validation.

A possible solution to the problem of water stress in the test plant would be to systematically replace the water of which the test plant is deprived. This could be achieved by instrumenting in the same way a neighbouring plant of similar dimensions. Instead of being directed to a collecting vessel, however, the water discharged could be fed to the soil under the plant being studied. Such paired interception trays might allow the acquisition of reliable estimates of  $I$  using long integration periods, without moisture stress being imposed on the test plant. Long-term shading of the soil surface by collecting devices, however, might still cause changes in soil temperature and moisture status, so that comprehensive testing of any such procedure would be required.

Using a canopy interception model constrained by data on  $C$  and on meteorological variables provides an alternative means to develop an estimate of  $I$ . The work of Domingo *et al.* (1998) appears to be the only study where this has been done for dryland plant communities, although they did not derive estimates of  $C$  by conventional direct measurement. Nevertheless, their data clearly show that evaporation from the shrub canopies proceeded continuously (and at rates of  $> 5$  mm/h) through monitored rain events, so exerting a dominant control on the aggregate interception loss. One of the difficulties facing the wider adoption of this approach is the limited availability of long time-series of relevant meteorological observations for dryland stations.

In summary, it appears that there is a need for additional work on the estimation of  $I$  values for dryland plant communities. Methods for direct observation are either difficult and in need of validation (the use of throughfall gauges and stemflow collars) or pose methodological problems of the kind outlined for the Serrato and Diaz (1998) collecting tray. Thus, there are few reliable estimates of community-level interception losses from drylands. Further work is required in this area, so that estimates of water balance relevant to the understanding of plant community structures (e.g. Dunkerley and Booth, 1999) can be made more secure, and so that hydrological models used to predict the outcome of contemporary environmental changes in drylands (e.g. the effects of nocturnal warming on vegetation change highlighted by Alward *et al.*, 1999) can be based upon data of good quality. It is also worth recalling that organic litter may cover 50% or more of dryland soil surfaces (Geddes and Dunkerley, 1999) and that litter, too, may be responsible for significant interception of water above the mineral soil (Putuhena and Cordery, 1996). In drylands, this interception remains to be assessed.

#### REFERENCES

- Alward RD, Detling JK, Milchunas DG. 1999. Grassland vegetation changes and nocturnal global warming. *Science* **283**: 229–231.
- Asdak C, Jarvis PG, Gardingen PV. 1998a. Evaporation of intercepted precipitation based on an energy balance in unlogged and logged forest areas of central Kalimantan, Indonesia. *Agricultural and Forest Meteorology* **92**: 173–180.
- Asdak C, Jarvis PG, van Gardingen P, Fraser A. 1998b. Rainfall interception loss in unlogged and logged forest areas of central Kalimantan, Indonesia. *Hydrological Processes* **206**: 237–244.
- Aston AR. 1979. Rainfall interception by eight small trees. *Journal of Hydrology* **42**: 383–396.
- Bouten W, Swart PJF, De Water E. 1991. Microwave transmission, a new tool in forest hydrological research. *Journal of Hydrology* **124**: 119–130.
- Bouten W, Schaap MG, Aerts J, Vermetten AWM. 1996. Monitoring and modelling canopy water storage amounts in support of atmospheric deposition studies. *Journal of Hydrology* **181**: 305–321.

- Crouse RP, Corbett ES, Seegrift DW. 1966. Methods of measuring and analyzing rainfall interception by grass. *Bulletin of International Association of Hydrological Sciences* **11**: 110–120.
- Domingo F, Sánchez G, Moro MJ, Brenner AJ, Puigdefábregas J. 1998. Measurement and modelling of rainfall interception by three semi-arid canopies. *Agricultural and Forest Meteorology* **91**: 275–292.
- Dunkerley DL, Booth TL. 1999. Plant canopy interception of rainfall and its significance in a banded landscape, arid western NSW, Australia. *Water Resources Research* **35**: 1581–1586.
- Dykes AP. 1997. Rainfall interception from a lowland tropical rainforest in Brunei. *Journal of Hydrology* **200**: 260–279.
- Gash JHC, Wright IR, Lloyd CR. 1980. Comparative estimates of interception loss from three coniferous forests in Great Britain. *Journal of Hydrology* **48**: 89–105.
- Gash JHC, Lloyd CR, Lachaud G. 1995. Estimating sparse forest rainfall interception with an analytical model. *Journal of Hydrology* **170**: 79–86.
- Geddes N, Dunkerley DL. 1999. The influence of organic litter on the erosive effects of raindrops and of gravity drops released from desert shrubs. *Catena* **36**: 303–313.
- Glover J, Gwynne MD. 1962. Light rainfall and plant survival in East Africa. I. Maize. *Journal of Ecology* **50**: 111–118.
- Glover PE, Glover J, Gwynne MD. 1962. Light rainfall and plant survival in E. Africa. II. Dry grassland vegetation. *Journal of Ecology* **50**: 199–206.
- Grah RF, Wilson CC. 1944. Some components of rainfall interception. *Journal of Forestry* **42**: 890–898.
- Hancock NH, Crowther JM. 1979. A technique for the direct measurement of water storage on a forest canopy. *Journal of Hydrology* **41**: 105–122.
- Hutjes RWA, Wierda A, Veen AWL. 1990. Rainfall interception in the Tai forest, Ivory Coast: application of two simulation models to a humid tropical system. *Journal of Hydrology* **114**: 259–275.
- Jetten VG. 1996. Interception of tropical rain forest: performance of a canopy water balance model. *Hydrological Processes* **10**: 671–685.
- Liu S. 1997. A new model for the prediction of rainfall interception in forest canopies. *Ecological Modelling* **99**: 151–159.
- Massman WJ. 1980. Water storage on forest foliage: a general model. *Water Resources Research* **16**: 210–216.
- Mauchamp A, Janeau JL. 1993. Water funnelling by the crown of *Flourensia cernua*, a Chihuahuan Desert shrub. *Journal of Arid Environments* **25**: 299–306.
- Merriam RA. 1961. Surface water storage on annual ryegrass. *Journal of Geophysics Research* **66**: 1833–1838.
- Návar J, Bryan R. 1990. Interception loss and rainfall redistribution by three semi-arid growing shrubs in northeastern Mexico. *Journal of Hydrology* **115**: 51–63.
- Nulsen RA, Bligh KJ, Baxter IN, Solin EJ, Imrie DH. 1986. The fate of rainfall in a mallee and heath vegetated catchment in southern Western Australia. *Australian Journal of Ecology* **11**: 361–371.
- Pressland AJ. 1973. Rainfall partitioning by an arid woodland (*Acacia aneura* F. Muell.) in south-western Queensland. *Australian Journal of Botany* **21**: 235–245.
- Putuhen WM, Cordery I. 1996. Estimation of interception capacity of the forest floor. *Journal of Hydrology* **180**: 283–299.
- Rutter AJ, Kershaw KA, Robins PC, Morton AJ. 1971. A predictive model of rainfall interception in forests, 1. Derivation of the model from observations in a plantation of Corsican pine. *Agricultural Meteorology* **9**: 367–384.
- Serrato FB, Diaz AR. 1998. A simple technique for measuring rainfall interception by small shrub: 'interception flow collection box'. *Hydrological Processes* **12**: 471–481.
- Specht RL. 1957. Dark Island Heath (nony-Mile Plant, South Australia). IV. Soil moisture patterns produced by rainfall interception and stemflow. *Australian Journal of Botany* **5**: 137–150.
- Stewart JB. 1977. Evaporation from the wet canopy of a pine forest. *Water Resources Research* **13**: 915–921.
- Teklehaimanot Z, Jarvis PG, Ledger DC. 1991. Rainfall interception and boundary layer conductance in relation to tree spacing. *Journal of Hydrology* **123**: 261–278.
- Thurow TL, Blackburn WH, Warren SD, Taylor CA. 1987. Rainfall interception by midgrass, shortgrass, and live oak mottes. *Journal of Range Management* **40**: 455–460.
- Tromble JM. 1983. Interception of rainfall by Tarbush. *Journal of Range Management* **36**: 525–526.
- Tromble JM. 1988. Water interception by two arid land shrubs. *Journal of Arid Environments* **15**: 65–70.
- Watanabe T, Mizutani K. 1996. Model study on micrometeorological aspects of rainfall interception over an evergreen broad-leaved forest. *Agricultural and Forest Meteorology* **80**: 195–214.
- West NE, Gifford GF. 1976. Rainfall interception by cool-desert shrubs. *Journal of Range Management* **29**: 171–172.
- Wigneron J-P, Calvet J-C, Kerr Y. 1996. Monitoring water interception by crop fields from passive microwave observations. *Agricultural and Forest Meteorology* **80**: 177–194.
- Wood MK, Jones TL, Vera-Cruz MT. 1998. Rainfall interception by selected plants in the Chihuahuan Desert. *Journal of Range Management* **51**: 91–96.