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Estimation of Canopy Storage Capacity as a Function of Leaf Area Index for use in Modeling Rainfall Interception

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Abstract

The canopy storage capacity term, S_{max}, used in estimates of rainfall interception in soil-plant-atmosphere models is often obtained empirically from measurements of rainfall interception in the vegetation canopy of interest. This approach limits the usefulness of models which are often developed for application in areas where measurements do not exist. The hypothesis that S_{max} should be directly related to the leaf area index (LAI) of the canopy was tested in order to develop a reliable parameter for storage capacity per unit leaf area, S_{lai}. Throughfall was measured on two broadleaf canopies and two needled canopies of high and low LAI over a four-month period in the Hudson River Valley, then resulting values for S_{lai} were tested in a simple simulation model. S_{lai} averaged 0.10 kg m^{-2} for the broadleaf plots and 0.33 kg m^{-2} for the needled plots but were not significantly different between leaf types. These values are in approximate agreement with estimates calculated from S_{max} measured in canopies with known LAI, but are substantially lower than the value of 1.0 kg m^{-2} often assumed in soil-plant-atmosphere models. Simulations show that using the average value of 0.2 kg m^{-2} gives reasonable results for estimates of rainfall interception for both broadleaf and needled forest canopies.

Key Words: Rainfall interception, Canopy storage capacity, model, Forest canopy

Introduction

The interception and re-evaporation of rainfall by plant canopies can constitute a significant portion of the total water budget in a soil-plant-atmosphere system, commonly in the range of 10% to 30% of precipitation. Intercepted rainfall evaporates from the surface of the canopy at rates up to four times higher than water which reaches the soil and participates in the transpiration component of evapotranspiration because of the comparatively low resistances encountered in the evaporation process (Stewart, 1977; Singh and Szeicz, 1979). Thus, in order to properly calculate the water budget in a vegetated system it is necessary to partition intercepted water from the total precipitation.

Factors that influence interception loses are rainfall rate and duration, the amount of water that can be held by the canopy, and evaporative demand during and after the rainfall event (Leonard, 1967). The amount of water potentially held by the canopy is a property of the vegetation architecture. Although there is some theoretical work outlining a method for calculating canopy storage capacity as a function of canopy architecture (Leonard, 1967), there is very little experimental work to support it. As one of the objectives of hydrology model development is to make predictions beyond the range of observations, theoretical approaches to estimating canopy storage capacity must be tested so that models of vegetation water dynamics can be applied broadly.

The most widely accepted models of rainfall interception divide incoming precipitation into a throughfall term, P_c, representing rain which passes directly through the canopy, and a storage term, S, which may be sub-divided into canopy storage, S_c, and stem storage, S_s. (Rutter et al., 1971; Rutter et al., 1975; Gash and Morton, 1978). The storage terms are limited by an estimate of the maximum amount of water that would remain on the canopy after drainage, S_{max}. S_{max} is usually determined according to the method outlined by Leyton *et al.* (1967) by plotting below canopy rainfall, P_c, against gross precipitation, P_o, for short, intense rainfall events for which one can assume minimal evaporation during the storm. By drawing a line with slope of 1 such that all the points are encompassed, the intercept of the curve is related to the storage capacity, which is calculated at $P_o = 0$.

The difficulty in using this empirical approach is that one needs to have interception measurements to parameterize the interception model. In order to use the model in a predictive mode, as is the case in regional climate or hydrology modeling, it is necessary to relate the canopy storage parameter to other, more readily quantified characteristics of the canopy such as leaf area index. Theoretical considerations indicate that one can define a canopy storage capacity as a quantity of water per unit leaf area (Leonard, 1967), which will be defined here as S_{lai}. Final storage capacity is thus dependent on average leaf area index. The value used for S_{lai} in a number of process models is 1 kg per m^2 of leaf area, equivalent to a millimeter depth of water on all leaf surfaces (GAPS, Riha *et al.*, 1994; NASA GISS Land Surface, Rosenzweig and Abramopoulos, 1996). It has been suggested that estimates of total interception losses in GCMs are generally high compared to local observations (Eltahir and Bras, 1993). One possible cause of an over-estimation is unrealistic parameterization of S_{max}.

Table 1 presents values of S_{max} found experimentally by the method of Leyton *et al.* (1967) and, where the information was reported, leaf area index of the study forest. In all these studies where it is not reported, one can assume leaf area indices higher than 1. In the two Sitka spruce (*Picea sitchensis*) forests reported by Gash *et al.* (1980), the first listed was planted in

1947 and the second in 1951, and, according the report, had closed canopy. Given that the tree densities of the two forests with reported leaf area indices of 2.3 and 4.9 were the lowest of all those reported, we may assume a very conservative average leaf area index of 2 for the rest of the forests in Table 1. Using this estimate and back-calculating the coefficient S_{lai} from their values of S_{max}, the average value of S_{lai} is 0.42 kg water m^{-2} leaf area, less than half the value often used in soil-plant-atmosphere models.

Experimental work designed to test S_{lai} for individual leaves of 5 tropical rainforest tree species (Herwitz, 1985) resulted in values ranging from 0.11 to 0.16 kg m^{-2}. It may be reasonable to assume that rainforest trees have particularly low storage rates per unit surface area because of the need to shed water from frequent rainfall (Herwitz, 1987; Lloyd *et al.*, 1988). Also, the experimental work of Herwitz (1985) determined the stem storage separately and found it to be significant, particularly for rough-barked tree species. Since the S_{max} values determined empirically from net and gross precipitation effectively include both leaf and bark storage, one may expect derived values of S_{lai} to be higher than when calculated for leaf surfaces alone. None the less, there is likely to be a relationship between leaf area and stem surface area (Causten, 1985), and thus estimates of canopy storage based on leaf area are reasonable.

Estimates based on the above review of the literature suggest that a reasonable value for S_{lai} may be at most about 0.4 kg m^{-2} rather than the commonly used 1 kg m^{-2}. This study was designed to estimate the value of S_{lai} for the determination of canopy storage capacity of northeastern coniferous and broadleaf forest with varying leaf area indices. Estimates are then tested with a model of forest energy and water dynamics for accuracy in predicting canopy throughfall.

Methods

Site measurements

Sites of varying leaf area index and leaf type were selected in the Black Rock Forest research area near Cornwall, NY in the Hudson River Valley. Two of the four stands chosen were composed of broadleaf hardwoods and two of coniferous tree species. The high leaf area index (LAI) broadleaf site was a pure stand of sixty year old Sugar Maple (*Acer saccharum*) with a density of approximately 1480 stems ha^{-1}. The high LAI needle-leafed site was a pure stand of Norway Spruce (*Picea abies*) planted 66 years ago, with a current density of 1480 stems ha^{-1}. The low LAI broadleaf site was dominated by Red Oak (*Quercus rubra*) of natural regeneration, while the low LAI needled site was of pure Red Pine (*pinus resinosa*) that had been thinned to very low densities over the years. All sites were on thin glacial till soils of poor quality which limited growth. Leaf area index was estimated using the light interception method (Decagon AccuPAR model PAR-80, Pullman WA) The four sites were within 0.5 kilometers of each other.

At each site, twelve plastic receptacles with funnel tops were fixed into position with stakes at a random spacing of approximately three meters. In an open area nearby, six additional receptacles were positioned to monitor reference rainfall. After each rainfall event, water accumulation in each container was measured with a graduated cylander and buckets were emptied. Of the sixteen rainfall events that were measured between July 23 and September 31, thirteen were considered appropriate for analysis according to the criteria defined by Leyton (1967), i.e., light, and of short duration in order to minimize the occurance of evaporation duing the event. One event was also removed from the broadleaf high LAI and both high and low LAI needled sites due to site disturbance.

Adapting the method of Leyton (1967), confidence intervals for S_{max} were determined for each site by plotting throughfall against precipitation external to the canopy and calculating the intercept term of the best-fit line rather than including all the points under the curve which places too much weight on possible outliers (Lloyd et al, 1988). Dividing through by the LAI for each site, estimates of S_{lai} were determined.

Weather variables were monitored at two nearby locations, a lowland site at 110 m in elevation and a ridgetop site at 365 m. Daily minimum and maximum temperature, precipitation, and solar radiation from these two sites were averaged to estimate meteorological conditions at the experimental site which was located at approximately 250 m in elevation. Event precipitation from the open reference site was used to adjust the precipitation measured at the weather stations to ensure the validity of the model comparisons to experimental interception.

Simulations

A model of energy and water balance for a homogeneous plant canopy, GAPS (Riha *et al.*, 1994), was used to test the calculated value for S_{lai}. The "Constant Cover" component of GAPS by-passes the photosynthesis calculations and is used primarily for estimation of forest water budgets. In this model, a simple representation of rainfall interception assumes that S_{max} is equal to S_{lai} multiplied by the LAI of the stand, and that precipitation is allowed to accumulate as canopy storage, S_c, until S_{max} is reached. Any precipitation above this level falls through or drains out of the canopy. Stem interception is assumed to be included in the canopy storage term. This model is a simplification of the standard Rutter-type model of rainfall interception (Rutter, 1975) in which canopy storage capacites analogous to "saturation" and "field capacity" are defined and drainage rate increases as the canopy becomes wetted. Implicit in the simpler

GAPS model is the assumption that drainage is instantaneous, and that no portion of any rainfall event which is smaller than the canopy storage capacity and occurs when the canopy is initially dry will reach the ground.

In these simulations, calculations of potential evapotranspiration were made at hourly time-steps with the Priestley-Taylor formulation (Priestley and Taylor, 1972). Evapotranspiration is divided into soil evaporation and canopy transpiration as a function of the fraction of light intercepted by the canopy. At each timestep, evaporation of intercepted rain is limited by the potential transpiration term but is assumed to take precedence over actual canopy transpiration. If potential transpiration is greater than the available S_c, S_c is reduced to zero and canopy transpiration is allowed to proceed at a rate limited by the timestep soil water availability. If potential transpiration is less than canopy storage, S_c is reduced by the amount of available energy and canopy transpiration is zero.

A further simplifying assumption of the GAPS model is that daily precipitation is distributed over the day in a pre-determined, user-defined manner which remains constant for all rainfall events. In these simulations, the daily rainfall total was distributed evenly over all hours of the day, which was only realistic for some of the days modeled. For example, if a rainfall event of 10 mm began at 4:00AM and ended at noon on a particular day, the simulated hourly rainfall would have been 0.42 mm hr^{-1} for 24 hours rather than the observed 1.25 mm hr^{-1} for six hours. This assumption should lead to prediction of higher rainfall interception and evaporation than observations, particularly if actual rainfall occurs predominantly during daytime when potential transpiration is relatively high.

Results

Site Measurements

Mean and standard deviation of leaf area indices and throughfall for each of the four plots are listed in Table 2. The standard error of the measured LAIs is higher in the low LAI broadleaf plots due to the extreme non-homogeneity of the canopy at this site. The percentage of precipitation lost as canopy interception averaged 29% over all plots and rainfall events, with a maximum of 65% for the lowest rainfall in the high LAI needled plots but approaching only 4% for the longer, high rainfall events.

Plots of throughfall, P_c, against event precipitation, P_o, are shown in Figures 1a-1d. The line minimizing deviations from the points is shown. Again, the sparseness and non-homogeneity of the canopy for the low LAI sites, particularly the low LAI broadleaf site, is evident in the large deviations from the best-fit line for those sites. Estimates of the slope and intercept term for the line describing the relationship are presented in Table 3. The slope is reasonably close to one for all four plots, as is expected theoretically. The intercept term, which represents whole canopy storage capacity, S_{max}, is largest for the high LAI needled plot. Dividing S_{max} by LAI to estimate S_{lai} resulted in a mean for the broadleaf plots of 0.10 kg m^{-2} and for the needled plots of 0.33 kg m^{-2}. The implication is that per unit leaf area interception is as much as three times higher for needles as for broadleaves. This result is expected theoretically due to the greater surface area per unit projected area. However, comparison of confidence intervals indicates that this difference is not significant. The large variance for the intercept in the low LAI broadleaf site, in particular, suggests some caution. Averaging needled and broadleaf results, the data indicates that S_{lai} is close to 0.2 kg m^{-2}, in reasonable agreement with estimates made from previous work cited earlier in this paper, and considerably lower than the standard of 1.0 kg m^{-2} often used in general water balance models.

Simulations

Values for S_{lai} of 1.0 kg m^{-2}, representing the standard often used, 0.2 kg m^{-2}, as the mean estimated for both leaf types in these tests, and 0.3 kg m^{-2} for needled canopies and 0.1 kg m^{-2} for broadleaf canopies, were tested in simulations of rainfall interception. Comparisons of simulated throughfall to measured values (Figures 2a-2d) show that interception is more sensitive to the value of S_{lai} at the high LAI sites, as might be expected, particularly at the high LAI broadleaf site. At the high LAI needled site, simulated throughfall is over predicted for large rainfall events and underpredicted for small rainfall events, indicating errors in the opposite direction for interception losses. This effect appears to be unrelated to the value of S_{lai}. Although using a value as high as 1.0 kg m^{-2} for S_{lai} leads to largest errors in all cases, there appears to be very little difference between using 0.2 kg m^{-2} for both broadleaf and needled canopies and using the mean estimated values of 0.1 for broadleaves and 0.3 for needles, even during the smaller rainfall events.

Discussion and Conclusions

The values found in this study for whole canopy storage capacity, S_{max}, are in general agreement with those found by others for similar forest types. Lankreijer *et al.* (1993) estimated 0.70 mm for a *Quercus rubra* stand with an LAI of 4.9. This compares with 0.50 mm found here for a broadleaf canopy having an LAI of 4.41. The value of S_{lai} calculated from their data is 0.14 kg m^{-2}, reasonably close to the value found here of 0.11 kg m^{-2}. Their value of S_{lai} for a pine forest with an LAI of 2.3 is 0.11 kg m^{-2}, lower than our needled site results which we estimate at

0.26 for the low LAI site and 0.40 for the high LAI site.

Although it is reasonable to expect S_{lai} to be higher for needled than for broadleafed canopies due to surface area considerations, the measurements in this study of LAI for the high LAI needled site may underestimate the real value. Using the light interception method for calculating LAI is most accurate at low leaf areas and begins to break down when most of the light is intercepted by the canopy. This limit should be reached at LAIs of about 5.0. There may also be error introduced as a result of the clumping of needles on whirls which will lead to underestimates of LAI in needled canopies when using the light interception method (Stenberg *et al.*, 1994). If the value measured here for the high LAI needled plot is lower than the real value, S_{lai} for this stand is overestimated.

The simulations performed here show that using a value of 1.0 kg m^{-2} for S_{lai} leads to an overprediction of rainfall interception in all cases but that the model is less sensitive to S_{lai} as LAI decreases. Using the mean value found here of approximately 0.2 kg m^{-2} for both canopy types resulted in reasonable estimates of interception over a range of rainfall events. The tendency to overpredict interception during small rainfall events, and underpredict during large events, seen in particular in the high LAI needled site, does not appear to be related to the value of S_{lai} used. Instead this may be a result of using the Priestley-Taylor equation to model potential evapotranspiration which does not account for the aerodynamics of the surface. This lack would tend to be most evident in needled canopies which are aerodynamically rough. Other simplifications in the interception model, however, may also have led to this result.

These results provide justification for the use of a smaller value for S_{lai} than has been commonly used in models of soil-plant-atmosphere water and energy balance when applied to canopies with unknown canopy storage capacity. Since models are being used more and more often in a predictive mode, such as is the case with general circulation models of global climate, correct paramaterization as a function of readily available features of the vegetation is important. Tests of the values found here by modeling interception in other tree species and canopy structures will be helpful in substantiating the generality of these results.

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Forest type	Leaf Area Index	Stems/ha	Smax(mm)	Source
Amazon rainforest	---	3000	0.74	Lloyd et al., 1988
Pinus pinaster	2.3	430	0.26	Lankreijer et al., 1993
*Pinus pinaster**		430	0.56	Gash et al., 1995
Quercus rubra	4.9	600	0.70	Lankreijer et al., 1993
Pinus sylvestris	---	800	0.80	Gash and Morton, 1978
Picea sitchensis	---	4250	1.20	Gash et al., 1980
Picea sitchensis	---	3600	0.75	Gash et al., 1980
Pinus sylvestris	---	1870	1.02	Gash et al., 1980
Quercus (mixed spp)	---	3000	0.80	Dolman, 1987
Mixed New Zealand rainforest	---	---	1.00	Pearce and Rowe, 1981
Pinus nigra	---	---	1.05	Rutter et al., 1975

Table 1: Reported estimates of canopy storage capacity, Smax, for various forest types.
* Gash et al., (1995) use the same pine forest at Les Landes, France, as Lankreijer et al., 1993, but calculate Smax on a per tree basis rather than averaging over spaces between trees.

	Open			B-high		B-low		N-high		N-low	
	mean	std		mean	std	mean	std	mean	std	mean	std
Event			LAI	4.41	0.32	1.73	0.71	4.8	0.4	2.75	0.25
1	14.7	0.7		12.3	1.4	13.5	1.6	11.0	2.5	10.8	0.7
2	1.8	0.5		1.7	0.4	1.6	0.4	0.6	0.4	1.1	0.4
3	6.0	0.2		5.3	0.4	6.5	0.5	4.1	0.9	5.6	1.6
4	3.9	0.1		2.9	0.5	2.0	0.6	1.4	0.5	2.3	0.6
5	12.4	0.2		9.6	1.1	7.2	1.7	8.5	2.4	9.2	0.6
6	27.8	1.7		25.1	2.9	26.8	2.8	22.7	3.3	22.8	3.5
7	8.6	0.3		9.2	0.8	----		3.8	1.2	7.8	1.1
8	19.8	1.2		15.2	2.6	18.7	3.1	10.4	3.1	13.8	4.6
9	2.6	0.2		1.6	0.2	2.3	0.3	----		----	
10	21.7	1.6		18.6	2.0	17.7	1.9	16.3	3.1	21.1	2.9
11	30.2	1.7		27.0	4.1	22.1	3.4	22.2	7.4	26.3	3.9
12	6.0	0.4		4.0	0.7	4.2	0.7	2.0	1.2	4.2	0.6
13	27.8	1.1		24.0	3.8	19.7	3.6	22.7	4.7	23.5	3.0

Table 2: Mean and standard deviation of leaf area index (LAI, m2/m2) and throughfall (mm) for broadleaf (B) and needled (N) sites measured for 13 rainfall events. For each canopied site and rainfall event, N=12. For the Open site, N=6. Blanks indicate datapoints removed from the analysis.

Site	N	Slope	Intercept (var)	R-squared	Estimated S-lai
B-high	13	0.89	-0.50 (0.49)	0.99	0.11
B-low	12	0.84	-0.16 (1.08)	0.95	0.09
N-high	12	0.81	-1.88 (0.79)	0.97	0.40
N-low	12	0.87	-0.73 (0.74)	0.98	0.26

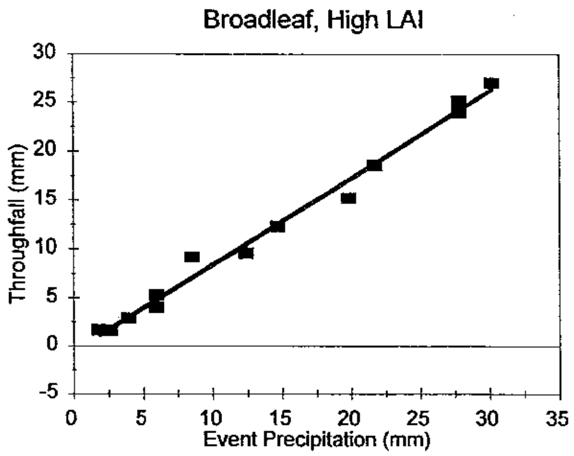
Table 3: Parameters for the equation of the best-fit line for the relationship between event precipitation and below-canopy throughfall for four sites. Slai is estimated from the intercept divided by the LAI at each site.

Figure Titles

Figure 1: Event precipitation versus throughfall for a) broadleaf high LAI, b) broadleaf low LAI, c) needled high LAI, and d) needled low LAI sites. The solid curve is the best-fit line of the data.

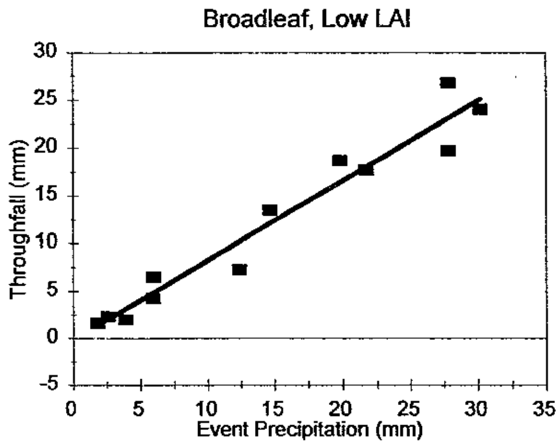
Figure 2: Observed versus simulated throughfall for a) broadleaf high LAI, b) broadleaf low LAI, c) needled high LAI, and d) needled low LAI sites, using three values of the per-unit leaf area storage term, S_{lai}. The value of 1.0 kg m^{-2} is often used in interception sub-models; for the broadleaf sites, 0.1 kg m^{-2} was the average found in this interception study, at the needled sites, the average was 0.3 kg m^{-2}, and 0.2 kg m^{-2} was tested as the average found here across both needled and broadleaf sites. The curve shown is the 1:1 line.

a.



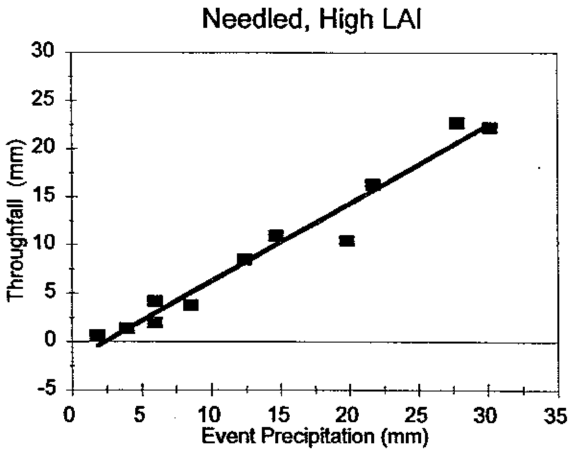
Broadleaf, High LAI

b.



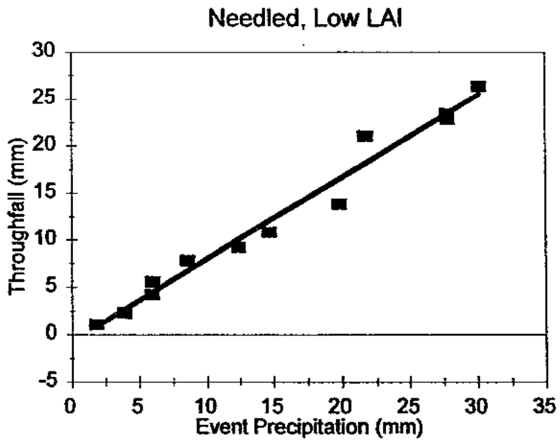
Broadleaf, Low LAI

c.

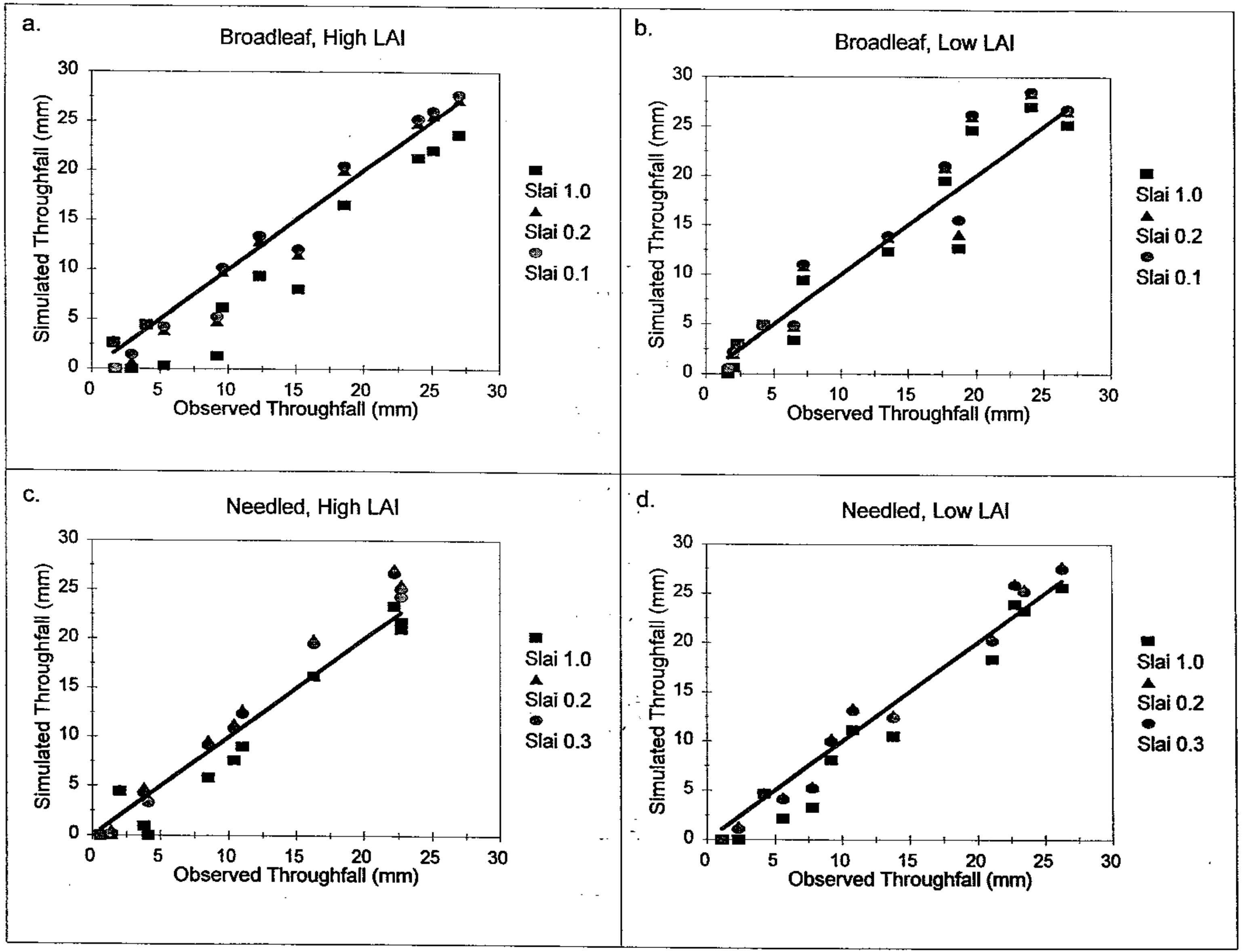


Needled, High LAI

d.



Needled, Low LAI


a.
Broadleaf, High LAI
b.
Broadleaf, Low LAI
c.
Needled, High LAI
d.
Needled, Low LAI
Simulated Throughfall (mm)
Observed Throughfall (mm)
0
5
10
15
20
25
30
■ Slai 1.0
▲ Slai 0.2
● Slai 0.1
● Slai 0.3