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Modelling crop canopy and residue rainfall interception effects on soil hydrological components for semi-arid agriculture[†]

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Abstract:

Crop canopies and residues have been shown to intercept a significant amount of rainfall. However, rainfall or irrigation interception by crops and residues has often been overlooked in hydrologic modelling. Crop canopy interception is controlled by canopy density and rainfall intensity and duration. Crop residue interception is a function of crop residue type, residue density and cover, and rainfall intensity and duration. We account for these controlling factors and present a model for both interception components based on Merriam's approach. The modified Merriam model and the current modelling approaches were examined and compared with two field studies and one laboratory study. The Merriam model is shown to agree well with measurements and was implemented within the Agricultural Research Service's Root Zone Water Quality Model (RZWQM). Using this enhanced version of RZWQM, three simulation studies were performed to examine the quantitative effects of rainfall interception by corn and wheat canopies and residues on soil hydrological components. Study I consisted of 10 separate hypothetical growing seasons (1991–2000) for canopy effects and 10 separate non-growing seasons (1991–2000) for residue effects for eastern Colorado conditions. For actual management practices in a no-till wheat–corn–fallow cropping sequence at Akron, Colorado (study II), a continuous 10-year RZWQM simulation was performed to examine the cumulative changes on water balance components and crop growth caused by canopy and residue rainfall interception. Finally, to examine a higher precipitation environment, a hypothetical, no-till wheat–corn–fallow rotation scenario at Corvallis, Oregon, was simulated (study III). For all studies, interception was shown to decrease infiltration, runoff, evapotranspiration from soil, deep seepage of water and chemical transport, macropore flow, leaf area index, and crop/grain yield. Because interception decreased both infiltration and soil evapotranspiration, no significant change in soil water storage was simulated. Nonetheless, these findings and the new interception models are significant new contributions for hydrologists. Published in 2006 by John Wiley & Sons, Ltd.

KEY WORDS rainfall interception; canopy; residue; water balance; infiltration; evaporation

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INTRODUCTION

During precipitation, interception by crop canopy and residue layer occurs; both canopy and residue interception are recognized as components in the hydrologic cycle that can affect the water and chemical balance components in a soil system by altering the amount of water entering the soil (Bristow *et al.*, 1986). Canopy and residue interception are considered losses to the system, as any rainfall intercepted by either of these components will subsequently be evaporated. Generally speaking, canopy interception is the amount of precipitation remaining on the leaf surface of the plant after throughfall and stemflow (Dunne and Leopold, 1978) and depends strongly on (1) vegetation type and stage of development, which can be characterized by the leaf area index (LAI), and (2) the intensity, duration, and frequency of rainfall or irrigation. Similarly, residue interception is a function of (1) residue type, mass, and areal cover and (2) the intensity, duration, and frequency of rainfall (Dingman, 1994).

Rainfall interception studies have concentrated on tree and grass systems, ignoring seasonal crops such as corn (*Zea mays*) and soybeans (*Glycine max*), because of the significantly longer duration of tree and grass canopy during the yearly hydrologic cycle (Savabi and Stott, 1994). However, Lull (1964) reported that, during a growing season, four different crop canopies intercepted 7 to 36% of seasonal rainfall (Table I). Additionally, the results of Konstorshchikov and Eremina (1963) indicated that growing wheat (*Triticum*) canopies can intercept between 10 and 25% of rainfall (Table I). Based upon the early data of Wollny reported by Baver (1938), significant rainfall interception over a growing season by corn, soybeans, and oats was observed with interception percentages of 22%, 35%, and 58% respectively (Table I).

With the introduction of conservation tillage methods to control soil erosion, crop residue can be present throughout the year, thereby imposing additional interception effects on an agricultural system. Using controlled laboratory studies, Savabi and Stott (1994) showed that corn and soybean residue could respectively intercept up to 29% and 23% of simulated rainfall (12·5 mm in 0·5 h). Therefore, the combined effect of crop canopy

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Table I. Summary of interception data in various crops (Kontorshchikov and Eremina, 1963; Lull, 1964)

Crop	Rainfall (mm)	Interception			Measurement period
		(mm)	(%)	(%)[a]	
Lull (1964) results for growing season					
Wheat	275	98	36		
Corn	181	28	16		
Soybean	158	23	15		
Oat	171	12	7		
Konstorshchikov and Eremina (1963) results					
Spring wheat				10–25	Growing season
Rye (50–150 cm high)				4–6	unknown dates
Oat				16	July
Oat				23	August
Baver (1938) results					
Corn				22	
Soybean				35	
Oat				58	

[a] Percentage of gross precipitation.

and residue interception on the hydrologic cycle can potentially preclude a high percentage (e.g. up to a maximum of 51% for corn for a single event) of rainfall from entering a soil profile depending on the crop, crop maturity and coverage, residue type and coverage, and rainfall intensity and duration for a rainfall event. Despite such empirical evidence for crop canopy and residue interception greatly affecting the amount of rainwater reaching the soil surface, there has been very little effort to model the aforementioned processes; nor has the effect of rainfall interception on different soil hydrological water balance components been investigated.

The objective of our study is to present and test a model extended from Merriam's (1960) approach for both crop and residue interception of rain, irrigation, and snowmelt. The canopy and residue interception models developed and the documented interception approaches used in other simulation models were examined relative to two field studies and one laboratory study. Upon validation, the canopy and residue interception components were added to the Agricultural Research Service's Root Zone Water Quality Model (RZWQM) model (Ahuja *et al.*, 2000) in order to examine the effect of interception on the water mass balance components and crop growth in an agricultural system. Two hypothetical studies were performed and analysed through RZWQM simulations to quantify the effects of interception on infiltration, runoff, water storage in the soil profile, evapotranspiration, macropore flow, deep seepage, and crop growth in a semi-arid environment, where interception may be more important. Additionally, a hypothetical RZWQM study was performed to examine the effects of interception on the partitioning of the water balance components in a wetter environment, i.e. higher frequency of low-intensity rainfall. This knowledge will help us understand and quantify interception and its subsequent effects on the hydrologic cycle, and crop growth.

Past modelling approaches

Detailed canopy interception models have been developed for dense forest systems (full canopy cover), most notably those of Rutter *et al.* (1971), Merriam (1960), and Gash (1979), but only simplistic approaches to canopy interception for sparse canopy vegetation, such as crops, have been included in soil–plant–atmosphere models. One such model is the Pesticide Root Zone Model (PRZM). This is a one-dimensional, finite-difference model that accounts for pesticide and nitrogen fate in the crop root zone, and accounts for canopy interception by reducing incoming rain by a crop-specific maximum storage depth (Carsel *et al.*, 1998). A second model, WAVES, is a one-dimensional daily time-step model that simulates the fluxes of mass and energy between the atmosphere, vegetation, and soil systems (Zhang and Dawes, 1998). WAVES includes the effect of maximum rainfall interception as follows:

$$I^{c}_{\max} = K_{r}\mathrm{LAI} \tag{1}$$

where K_r (m) is the rainfall interception coefficient and LAI refers to the canopy layer. The coefficient K_r is a fitting parameter that ranges from 0·0003 to 0·002, depending on crop growth. A third model, the CropSyst Crop Production Model, is a crop growth simulation model that accounts for canopy interception I^c (metres of water) as a function of crop canopy cover c^c (no units) (Campbell and Diaz, 1988):

$$I^{c} = 0{\cdot}001c^{c} \tag{2}$$

Of the above computer models, only CropSyst includes maximum residue interception $I^{r}_{\max}$ (millimetres of water) as such:

$$I^{r}_{\max} = a_{r}\mathrm{RM} \tag{3}$$

where RM (kg ha^{-1}) is residue mass and a_r is an empirical coefficient, equal to 4×10^{-4} mm ha kg^{-1} (Bristow *et al.*, 1986). This maximum water storage is met before the incoming precipitation infiltrates into the soil layers. This same principle was used by Andales *et al.* (2000) with a slightly different a_r value of $3{\cdot}8 \times 10^{-4}$ mm ha kg^{-1}.

Similar approaches have been used with respect to other soil–plant–atmosphere models. However, these models can oversimplify the process of interception. Evaporative loss during the storm event from water intercepted by canopy and residue is not considered. Canopy interception calculations do not account for the effects of the amount of precipitation and the combination of crop canopy cover and leaf area. Additionally, most models reviewed do not include rainfall interception by residue. The method suggested by CropSyst does not account for depth of precipitation, residue cover, or residue type.

Recently, van Dijk and Bruijnzeel (2001a) developed a more detailed canopy interception model adapted from the Gash (1979) model, herein called the van Dijk model. Gash (1979) and van Dijk and Bruijnzeel (2001a) considered rainfall to occur as a series of discrete events, during which three phases could be distinguished: (1) a wetting phase during which rainfall P is less than the threshold value P' required to saturate the canopy; (2) a saturation phase (provided rainfall intensity R exceeds the evaporation rate from the wet canopy E_j; and (3) a drying phase after rainfall has ceased. The vegetation structure is described in terms of a canopy capacity S_v, which is defined as the amount of water left on a saturated canopy under zero evaporation conditions after rainfall and canopy drainage have ceased. Van Dijk and Bruijnzeel (2001a) applied these conditions and determined the rainfall necessary to saturate the canopy P'_j (mm) to be

$$P'_j = -\frac{RS_{v,j}}{E_j}\ln\left(1 - \frac{E_j}{c_jR}\right) \tag{4}$$

j is the storm event (unitless) and c_j is the canopy cover fraction (unitless).

For m storms insufficient to saturate the canopy ($P \leq P'$):

$$I_L = \sum_{j=1}^{m} c_jP_j \tag{5}$$

where I_L (mm) is the total depth of interception loss and P_j (mm) is the depth of the rain event. For n storms sufficient to saturate the canopy ($P > P'$), the total interception is the sum of three stages, namely

wetting up the canopy:

$$I_{L1} = \sum_{j=1}^{n}\{c_jP'_j - S_{v,j}\} \tag{6a}$$

wetting canopy evaporation during storm:

$$I_{L2} = \sum_{j=1}^{n}\frac{E_j}{R}\{P_j - P'_j\} \tag{6b}$$

evaporation after rain ceases:

$$I_{L3} = \sum_{j=1}^{n} S_{v,j} \tag{6c}$$

where

$$I_L = I_{L1} + I_{L2} + I_{L3} \tag{7}$$

Van Dijk and Bruijnzeel (2001b) applied this model to two field studies. A 1994–1995 study (study 1) examined a maize–rice–cassava (*Z. mays–Oryza sativa–Manihot esculenta*) system for 124 days where 1577 mm of rain fell over the growing period. A 1998–1999 study (study 2) examined a maize–cassava system for 196 days where 1642 mm of rain fell over the growing period. The predicted interception loss for study 1 was 299·1 mm (19% of total rainfall) and the predictive loss for study 2 was 130·1 mm (8% of total rainfall). These simulated values were within 2·5% and 1·5% respectively of the field-measured interception data.

Although the van Dijk model performed very well relative to the above studies, the variables needed for evaluation are difficult to estimate and can be computationally expensive. According to van Dijk and Bruijnzeel (2001a), the maximum storage capacity needed in Equations (4), (6a) and (6b) is almost entirely based on leaf storage, which is a species-specific term and may not be available. Likewise, the evaporation rate of the water intercepted by the canopy during the storm is a function of a coefficient referred to as the energy exchange coefficient between the canopy and atmosphere; again, this coefficient may not be readily attainable. Finally, the model does not account for fallen leaves and litter that may also intercept rain (residue interception).

Therefore, there is a need to develop (1) a canopy interception model that uses fewer variables than the van Dijk model and attempts to be non-crop specific with respect to canopy interception; and (2) a more mechanistic residue interception model than the one used in CropSyst. Additionally, a more mechanistic approach to rainfall interception is needed. With these combined processes in a comprehensive water balance and crop growth model, such as RZWQM, the effect on the water balance and its components can be investigated.

MODEL DEVELOPMENT

Partitioning the water balance components

Because the water balance is expected to be affected by canopy and residue interception, its components are examined. A change in soil water storage S over a given depth D and time period can be defined as

$$\Delta S_D = P - Q - E - T - G \tag{8}$$

where P is precipitation, Q is surface runoff, E is total evaporation, T is transpiration by plant, and G is 'deep seepage' at depth D. Here, the control volume is defined by fluxes across surfaces above the canopy, at the bottom of the soil profile, and the differential lateral runoff. Total evaporation E can be further partitioned as

$$E = E^{s} + E_{i}^{c} + E_{i}^{r} \tag{9}$$

where E^{s} is evaporation from bare soil, E_{i}^{c} is evaporation from canopy interception, and E_{i}^{r} is evaporation from residue interception.

Dropping the subscript D in S_D, and adding a subscript to denote interception (i) or no interception (0) for relevant components, we get

$$\Delta S_0 = P - E_0 - T_0 - Q_0 - G_0 \tag{10a}$$

$$\Delta S_{i} = P - E_{i} - T_{i} - Q_{i} - G_{i} \tag{10b}$$

For the case of interception being simulated over long time periods, or possibly water year to water year, we may assume $\Delta S_{i} = \Delta S_0 = 0$. Although this is not exactly the case in our results below, it can be assumed for simplicity, and in fact $\Delta S_i \approx \Delta S_0$. Furthermore, if $DS_{i} = DS_0$, then we can subtract Equation (10a) from Equation (10b) to get

$$Q_0 + E_0 + T_0 = Q_{i} + E_{i} + T_{i} \tag{11}$$

Thus, if water content and deep drainage remain relatively unchanged by interception (see below), then the effects are primarily on the partitioning between R, E, and T. Infiltration I can also be considered simply by raising the lower boundary of the water balance control volume to the ground surface and replacing DS with I and setting $\Delta S_{i} = \Delta S_0$ in Equations (10a) and (10b). Then:

$$Q_0 + E_0 + T_0 + I_0 = Q_{i} + E_{i} + T_{i} + I_{i} \tag{12}$$

where Equation (9) is evoked to partition evaporation further. Equations (10) and (12) serve as the bases for analyses of water balance partitioning here.

Modified Merriam canopy interception model development and testing

Having examined the effects of interception on the water balance, a new approach to quantifying interception is evaluated. Leonard (1965) described the theory of the interception process and suggested that gross interception loss by a canopy I^{c} can be expressed in terms of water per unit ground projected area:

$$I^{c} = S^{c} + c^{c}E^{c}(\Delta t) \tag{13}$$

where S^{c} [L] is water stored on the vegetative canopy at the end of rain event, c^{c} is canopy coverage (unitless), E^{c} [L] is canopy evaporation rate during rain event, and Δt [T] is duration of rain event.

Merriam (1960) suggested that the maximum canopy saturation was approached exponentially as cumulative rainfall increased:

$$S^{c} = S_{\max}^{c}(1 - e^{-P/S_{\max}^{c}}) \tag{14}$$

where $S_{\max}^{c}$ [L] is the maximum storage capacity of canopy over projected area given full canopy cover.

The Merriam model was originally developed for forest systems with full ground cover. Equation (14) was modified by including canopy coverage, giving the modified Merriam model:

$$S^{c} = c^{c}S_{\max}^{c}(1 - \mathrm{e}^{-P/S_{\max}^{c}}) \tag{15}$$

According to Rutter *et al.* (1971), evaporation from partially wet canopies is assumed to be proportional to water storage S^{c} on the canopy:

$$E^{c} = \frac{S^{c}}{S_{\max}^{c}}E^{wc} \tag{16}$$

where E^{wc} (cm) is the wet canopy evaporation; and where the Penman–Monteith equation is used (Klassen, 2001):

$$\lambda E^{wc} = \frac{\Delta R_{n} + \rho c_p(\mathrm{VPD}_0/r_{a})}{\Delta + \gamma} \tag{17}$$

λ (J kg^{-1}) is the latent heat of vaporization, Δ (kPa K^{-1}) is the slope of the saturation vapour pressure versus temperature curve, R_{n} (W m^{-2}) is the net radiation above canopy, ρc_p (J K m^{-3}) is the volumetric heat capacity of air, VPD$_0$ (kPa) is the air vapour pressure deficit at the mean canopy height, r_{a} (s m^{-1}) is the atmospheric transport resistance, and γ (kPa K^{-1}) is the psychrometric constant.

One of the goals of the study was to view the maximum storage capacity of the canopy $S_{\max}^{c}$ as non-crop specific. Two methods for calculating $S_{\max}^{c}$ (mm) based on the LAI of the crop were reviewed (von Hoyningen-Huene, 1981):

$$S_{\max}^{c} = 0{\cdot}935 + 0{\cdot}498(\mathrm{LAI}) - 0{\cdot}005\,75(\mathrm{LAI}^2) \tag{18a}$$

and (Brisson *et al.*, 1998):

$$S_{\max}^{c} = 0{\cdot}2(\mathrm{LAI}) \tag{18b}$$

Thus, with increasing LAI during crop growth and decreasing LAI during senescence, $S_{\max}^{c}$ will increase and decrease respectively.

Modified Merriam residue interception model development and testing

The modelling of rainfall interception I^{r} by residue is approached in the same manner discussed above where,

$$I^{r} = S^{r} + c^{r}E^{r}(\Delta t) \tag{19}$$

S^{r} [L] is the water stored on the crop residue at the end of rain event, c^{r} is the residue coverage (unitless), E^{r} [L] is the residue evaporation during rain event, and Δt [T] is the duration of rain event.

Following the Merriam (1960) theory, maximum residue saturation is approached exponentially as cumulative rainfall increases:

$$S^{r} = c^{r}S_{\max}^{r}\left\{1 - \exp\left[\frac{-a^{r}(P - S^{c})}{S_{\max}^{r}}\right]\right\} \tag{20}$$

S^{r}_{max} [L] is the maximum storage capacity of residue given full residue cover, c^{r} (unitless) is the residue cover, and a^{r} (unitless) is the crop-specific empirical parameter. Here, S^{r}_{max} reflects the residue type and mass. Additionally, as residue is added or decays over time, residue interception will increase or decrease, respectively.

Evaporation of a partially wet residue is assumed to be proportional to water storage S^{r} on the residue:

$$E^{r} = \frac{S^{r}}{S^{r}_{max}} E^{wr} \tag{21}$$

where, according to Shuttleworth and Wallace (1985):

$$\lambda E^{r} = \frac{\Delta(R_{nr} - G_{r}) + \rho c_{p}(\mathrm{VPD}_{0}/r^{r}_{a})}{\Delta + \gamma\left(1 + \dfrac{{r_{s}}^{s} + {r_{s}}^{r}}{{r_{a}}^{r}}\right)} \tag{22}$$

where R_{nr} (W m^{-2}) is the net radiation over bare soil and residue, G_{r} (W m^{-2}) is the heat flux into the residue, r^{r}_{a} (s m^{-1}) is the aerodynamic resistance between the residue and mean canopy height, r^{s}_{s} (s m^{-1}) is the soil surface resistance, and r^{r}_{s} (s m^{-1}) is the surface resistance of the residue.

The maximum residue storage capacity S^{r}_{max} is a crop-specific parameter. According to a study by Savabi and Stott (1994), the amount of total interception or maximum storage capacity is a function of the amount and type of residue. Under varying rainfall intensities and a range of residue mass (2·9–17·8 t ha^{-1} for corn, 1·2–5·9 t ha^{-1} for soybean, 2·9–11·0 t ha^{-1} for wheat), a quadratic equation was fitted to the total interception amounts measured, giving:

$$\begin{aligned} S^{r}_{max}\ (\mathrm{mm}) &= 346\mathrm{RM} - 10{\cdot}5\mathrm{RM}^{2}\ (\text{corn}) \\ S^{r}_{max}\ (\mathrm{mm}) &= 370\mathrm{RM} - 11\mathrm{RM}^{2}\ (\text{soybean}) \\ S^{r}_{max}\ (\mathrm{mm}) &= 627\mathrm{RM} - 37{\cdot}3\mathrm{RM}^{2}\ (\text{wheat}) \end{aligned} \tag{23}$$

where RM (kg ha^{-1}) is the residue mass at time t. Equation (23) was developed over a uniform area. Thus, RM reflects the thickness of the residue.

If a different crop type is used in the simulation and is comparable to either corn, soybean, or wheat, then Equation (23) can be used; otherwise, the following generic form is used (Arreola Tostado, 1996):

$$S^{r}_{max} = a_{w}\mathrm{RM} \tag{24}$$

a_{w} is an empirical coefficient ($3{\cdot}55 \times 10^{-4}$ mm ha kg^{-1}).

Savabi and Stott (1994) applied Equations (20) and (23) to a laboratory study in order to determine a^{r}. Two studies of varying residue mass and rainfall rate were performed for three individual crop residue types: corn, soybean, and wheat. The first study consisted of an air-dried mass of 5959 kg ha^{-1} of each crop, which was spread evenly over a mesh screen on a 0·41 m^{2} plot and exposed to a rainfall rate of 25 mm h^{-1} for a period of 0·5 h. The second study used 5949 kg ha^{-1}, and a rainfall rate of 50 mm h^{-1} was applied for 0·5 h. The study plots were designed so that the rate of rainfall passing through the residue could be measured below the residue by a collector. The cumulative experimental data for interception was plotted with respect to the cumulative water applied, and Equation (20) was fitted by adjusting a^{r}. The results of both studies are shown as symbols in Figure 1. Based on the fitted curves, the a^{r} values for corn, wheat, and soybean were determined to be 0·5, 1·25, and 1·25 respectively. A value of 1·0 is used for a generic crop.

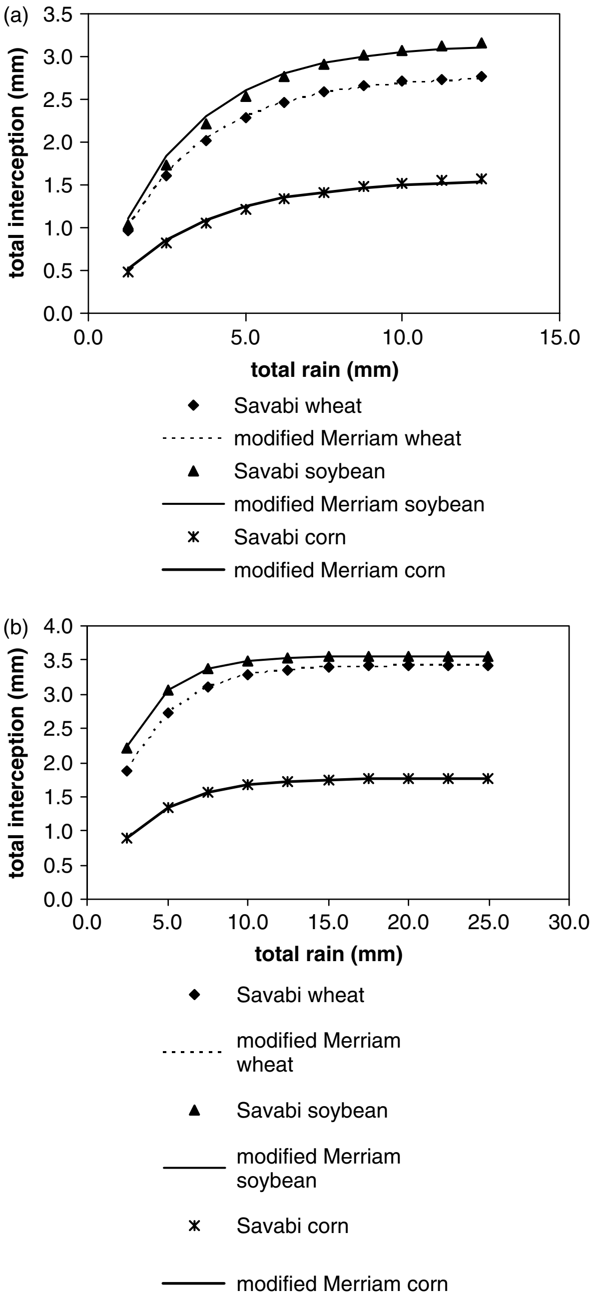

Figure 1. Modelled and experimental results of: (a) cumulative residue interception and cumulative rainfall for a rainfall rate of 25 mm h^{-1} and a residue mass of 5949 kg ha^{-1} from the Savabi and Stott (1994) study; (b) cumulative residue interception and cumulative rainfall for a rainfall rate of 50 mm h^{-1} and a residue mass of 5650 kg ha^{-1} from the Savabi and Stott (1994) study

Inclusion of canopy and residue interception model in RZWQM

The equations of interest (Equations (13)–(24)) were coded into the RZWQM model. Applying the above equations, a total depth of interception can be quantified after a rain event given the rainfall intensity and duration, crop type and maturity, residue type, and residue mass. In RZWQM, the depths of rain intercepted by crop and residue that are not evaporated during the storm, i.e. S^c and S^r, are assumed to be evaporated the following computational day:

$$E_i^c = S^c \qquad (25a)$$

$$E_i^r = S^r \qquad (25b)$$

E_i^c [L] is the depth of evaporated water from the water stored on canopy post rain event and E_i^r [L] is the depth of evaporated water from the water stored on residue post rain event.

These intercepted amounts are considered to precede the canopy transpiration with respect to E_i^c and soil evaporation with respect to E_c^r. Therefore, the amount of intercepted rainfall by the crop canopy and residue reduces the potential transpiration T_p and potential soil evaporation E_p^s:

$$\text{Net } T_p = T_p - E_i^c \qquad (26a)$$

$$\text{Net } E_p^s = E_p^s - E_i^r \qquad (26b)$$

Both reservoirs can also effectively intercept irrigation applications. Four types of irrigation are considered in RZWQM: sprinkler, furrow, flood, and drip irrigation. Sprinkler irrigation is approached as simulated rainfall substituting P with the depth of irrigation IR. Because the other methods of irrigation are applied at the soil surface level, only sprinkler irrigation can be affected by canopy interception. Residue can actively intercept sprinkler, furrow, and flood irrigation applications. Drip irrigation is not considered, as this method delivers water directly to the soil. If flood or furrow irrigation is used, then

$$\begin{aligned} S^r &= S^r_{\max} \qquad (\text{IR} > S^r_{\max}) \\ S^r &= I_{rr} \qquad (\text{IR} \le S^r_{\max}) \end{aligned} \qquad (27)$$

The following assumptions are made with respect to including canopy and rainfall residue interception into RZWQM.

1. Once the water is in each reservoir (canopy and residue), it is immobilized until evaporation. There is no gravitational drip from the canopy or seepage through the residue.
2. The effect of wind on the trajectory of rainfall is not considered.
3. The geometries of the canopy leaves and residue are not considered.
4. Snowfall is not considered explicitly, but snowmelt may be intercepted.

METHODS AND MATERIALS

Modified Merriam residue and canopy rainfall interception model testing

The results of two field studies (A and B) were investigated to test the modified Merriam canopy interception model. Both methods of maximum canopy storage capacity (Equations (18a) and (18b)) were input into Equation (15) and applied to the field studies in order to determine which method provided the best results. The van Dijk model was examined and compared with the modified Merriam model. Much like the modified Merriam model, both methods for calculating $S^c_{\max}$ are reviewed, where $S_{v,j}$ is replaced by $S^c_{\max}$. Alternative approaches to canopy interception suggested by PRZM, WAVES, and CropSyst were also investigated.

Study A (Leuning *et al.*, 1994) was an experimental study of growing wheat on a 5 ha field from May to November 1991 in Wagga Wagga, Australia. Peak LAI reached during the growing season was 3·9, and precipitation and interception measurements were made between 13 August and 7 November. For the purpose of the current study, the average rainfall duration per event was assumed to be 2 h, and the pan evaporation rate was used for the wet canopy evaporation rate. Accordingly, the canopy evaporation rate ranged from 0·15 to 0·56 mm per event (~25·6% of the total rainfall) over the course of the study period.

Study B (Steiner *et al.*, 1983) was an experimental study with growing corn on several plots of land from 1980 to 1981 (plots B1–B4) in Garden City, Kansas. Peak LAI during measurements was >3·0, and precipitation and interception measurements were made between July 1980 and September 1981. The pan evaporation rate was used for the wet canopy evaporation rate and ranged from 0·35 to 0·54 mm per event (~9·3% of total rainfall) over the course of the study period. Cumulative precipitation depths for plots B1–B4 were 88·1 mm, 80·3 mm, 85·9 mm, and 148·8 mm respectively.

In order to validate the modified Merriam residue interception model, Equation (20) was applied to a residue interception study by Mohamoud and Ewing (1990) (study C). An average mass of 3·71 Mg ha^{-1} of dry corn residue was spread evenly on meshed screens (0·92 m^2). A rainfall simulator applied water to the residue samples at intensities of 25·4, 63·5 and 127 mm h^{-1} for 1 h (plots C1–C3). The approach to residue interception suggested by CropSyst was also investigated.

RZWQM studies to evaluate interception effects in a semi-arid environment

Three studies were performed using RZWQM to evaluate the effects that canopy and residue interception have on an agricultural system. Hypothetical study I is comprised of a 300 cm loam profile with the soil hydraulic properties estimated according to Rawls *et al.* (1982). The soil system was subjected to Akron, Colorado, meteorological and rainfall data from 1991 to 2000 (10 years). The Akron data reflect dryland agriculture with low precipitation. RZWQM simulations were performed for 10 growing seasons (1 May to 9 August for each year) to examine canopy interception (study IA) and 10 non-growing seasons (9 August to 1 May the following year) to examine residue interception effects (study IB). For the growing seasons, two scenarios were considered: sweetcorn growth (100 days annual growing period beginning in May) with and without canopy interception. The growing-season studies were performed using RZWQM's Quickplant option. Quickplant allows the user to set maximum leaf area, maximum root depth, maximum crop height, and other parameters. The crop is allowed to grow optimally to the set parameters (Table II) regardless of water or plant stresses. Other input parameters for the canopy interception part of the study are summarized in Table III. RZWQM is executed with and without the interception option.

Two scenarios were also considered for the non-growing seasons: 10 Mg ha^{-1} of corn residue with and without residue interception. The input parameters for the residue interception part of the study are summarized in Table II. For growing seasons (canopy interception effects) and non-growing seasons (residue interception effects), the simulation results of net precipitation (Net $P = P - I^{c} - I^{r}$), canopy interception I^{c}, residue interception I^{r}, infiltration I, runoff Q, change in water storage ΔS, deep seepage DS, evaporation from soil E^{s}, evaporation from residue E_{i}^{r}, evaporation from canopy E_{i}^{c}, and transpiration T were examined. RZWQM is executed with and without the interception option.

Table II. Quickplant parameters for canopy interception study (study IA)

Parameter	Value
Vegetation	Sweetcorn
Growing season length (days)	100
Maximum LAI	4·0
Maximum crop height (cm)	200
Maximum root depth (cm)	150
Total seasonal nitrate uptake (kg ha^{-1})	100
C : N ratio of fodder material	25 : 1

Table III. Input and meteorological data for RZWQM for canopy and residue interception study (studies IA and IB)

Parameter	Canopy interception (IA)	Residue interception (IA)
Years of simulation	1991–2000	1991–2000
Start date	1 May	10 August
End date	9 August	30 April
Soil type	Silt loam	Silt loam
Initial water content	0·200	0·100
Soil profile depth (cm)	300	300
Fraction of porosity as macropores	0·10	0·10
Residue type	NA	Corn
Residue mass (Mg ha^{-1})	NA	10.0
Meteorological and rainfall data	Akron, CO	Akron, CO

Study II was performed using the real management practices in a no-till corn–fallow–wheat cropping system and the actual meteorological data for a continuous 10-year period (1991–2000) at Akron, Colorado (Bowman and Halvorson, 1997; Anderson *et al.*, 1999). An initial winter wheat residue cover was measured as 3 Mg ha^{-1}, and no tillage practices were employed. The management practices and input parameters for the study are summarized in Table IV. Additionally, a non-reactive, non-absorbing bromide tracer (100 kg ha^{-1}) was added to the soil surface at the start of simulation. Two simulations were performed in this study: with canopy and

Table IV. Management practices input data for RZWQM for Akron, Colorado, study (study II)

Parameter	Corn	Wheat
Years of simulation	1991–2000	1991–2000
Growing season (planting date–harvest date)	29 Apr–6 Oct 1993 1 May–11 Oct 1996 7 May–6 Oct 1999	9 Sep 1991–8 Jul 1992 20 Sep 1994–26 Jul 1995 19 Sep 1997–30 Jun 1998 19 Sep 2000–8 Jul 2001
Stubble height (cm)	15·0	5·0
Seed planting density (ha^{-1})	16 000	900 000
Row spacing (cm)	76	19
Years of simulation	1 Jan 92–31 Dec 2001	
Soil type, depth (cm)	Loam, 0–15 Clay loam, 15–30 Sandy loam, 30–178	
Fraction of porosity as macropores	0·10	
Initial water content, depth (cm)	0·3404, 0–15 0·3406, 15–30 0·3104, 30–178	
Initial residue type	Wheat	
Initial age of residue (days)	200	
Residue mass (t ha^{-1})	3·0	
Meteorological and rainfall data	Akron, CO	

residue interception, and without interception. The simulation results of net precipitation, snowmelt (SM), change in water storage, runoff, infiltration, deep seepage, macropore flow (MF), canopy and residue interception, and evapotranspiration were examined with respect to the water balance of the system. The LAI, yield, and crop biomass were also examined and compared with measured field results. Finally, the hypothetical effects of the two simulations on a bromide tracer were examined with respect to the residual bromide in the soil and the deep seepage of bromide. Again, RZWQM is executed with and without the interception option, and the generic plant growth model was used to simulate wheat and corn crops.

Study III was performed using theoretical management practices in a corn–fallow–wheat cropping system using meteorological data for a continuous 6-year period (1998–2003) at Corvallis, Oregon, in order to examine a wetter environment, i.e. high frequency of low rainfall events. An initial winter wheat residue cover was assumed to be 3 Mg ha^{-1}, and no tillage practices were employed. The management practices and input parameters for the study are summarized in Table V. Two simulations were performed in this study: with canopy and residue interception, and without interception. The simulation results of net precipitation, water storage, runoff, infiltration, deep seepage, canopy and residue interception, and evapotranspiration were examined with respect to the water balance of the system. The LAI and yield were also examined. RZWQM with the generic plant growth model for wheat and corn was executed with and without the interception option.

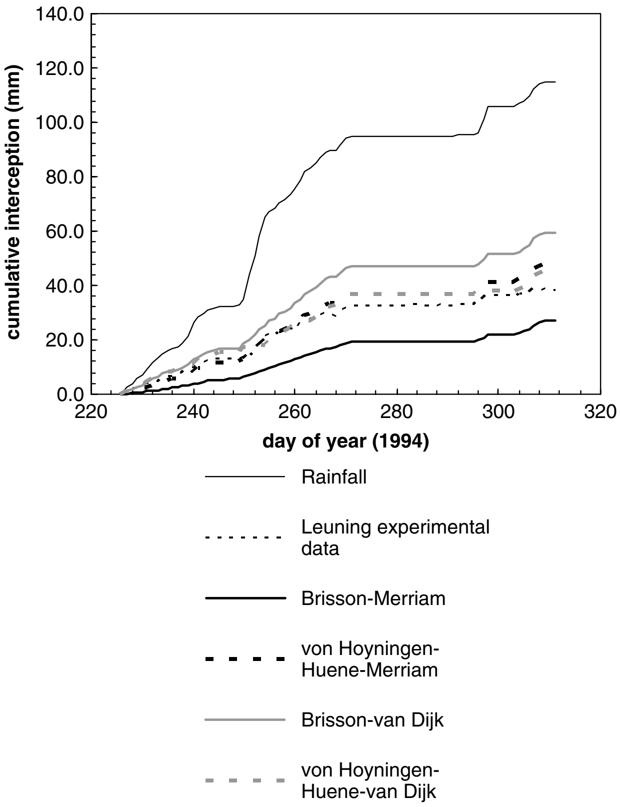

Figure 2. Temporal plot of cumulative rainfall, measured cumulative interception, von Hoyningen-Huene–Merriam modelled interception, and Brisson–Merriam modelled interception, von Hoyningen-Huene–van Dijk modelled interception, and Brisson–van Dijk modelled interception for the Leuning *et al.* (1994) study

RESULTS AND DISCUSSION

Canopy and residue interception model testing and validation

The simulation results of the modified Merriam canopy model and the van Dijk model were compared with the experimental field results of Leuning *et al.* (1994) (study A). The cumulative precipitation and modelled cumulative interception depths for both the von Hoyningen-Huene (1981) and Brisson *et al.* (1998) methods of maximum canopy storage (Equations (18a) and (18b)) are shown in Figure 2. (Note: the von Hoyningen-Huene–Merriam and von Hoyningen-Huene–van Dijk lines overlap each other for most of the time period studied.) The von Hoyningen-Huene method for calculating $S^{c}_{\max}$ provided modelled results closer to those of the experimental results than the Brisson method in both the modified Merriam model (Equations (13), (15), and (16)) and the van Dijk model (Equations (6) and (7)). The modified (von Hoyningen-Huene) Merriam model produced slightly better results at the beginning of the simulation relative to the van Dijk model, whereas the van Dijk model produced better results towards the

Table V. Hypothetical management practices input data for RZWQM for Corvallis, Oregon, study (study III)

Parameter	Wheat	Corn
Years of simulation	1998–2003	1998–2003
Growing season (planting date–harvest date)	15 Sep 1999–24 Jun 2000 15 Sep 2001–24 Jun 2002	1 Jun 1998–26 Nov 1998 1 Jun 2000–26 Nov 2000
Stubble height (cm)	15·0	5·0
Seed planting density (ha^{-1})	16 000[1]	900 000
Row spacing (cm)	80 cm	20 cm
Soil type	Chehalis silty clay loam	
Fraction of porosity as macropores	0·10	
Initial water content, depth (cm)	0·2969, 0–298	
Initial residue type	Wheat	
Initial age of residue (days)	200	
Residue mass (t ha^{-1})	3·0	

Table VI. RMSEs between observed and modelling results for cumulative canopy and residue interception for two field studies and one laboratory study: study A (Leuning *et al.*, 1994), study B (Steiner *et al.*, 1983), and study C (Mohamoud and Ewing, 1990)

	RMSE (mm)									
	Canopy interception								Residue interception	
	VHH[a]–Merriam	Brisson–Merriam	VHH[a]–van Dijk	Brisson–van Dijk	PRZM	WAVES 1[b]	WAVES 2[c]	CropSyst	Modified Merriam	CropSyst
Study A	3·98	11·30	3·27	11·93	17·71	25·09	19·74	3·90		
Study B1	1·50	5·28	5·56	5·53	1·44	1·44	5·83	4·72		
Study B2	1·46	2·36	2·61	2·56	2·97	2·97	2·91	1·78		
Study B3	2·60	8·89	9·29	9·25	3·95	3·95	9·66	8·52		
Study B4	2·79	8·48	8·72	8·65	1·64	1·64	9·31	7·58		
Average	2·47	7·26	5·89	7·58	5·54	12·31	6·88	5·30		
Study C1									0·20	1·18
Study C2									0·44	1·28
Study C3									0·44	1·26
Average									0·36	1·24

[a] VVH: von Hoyningen-Huene.
[b] $K = 0{\cdot}001$ m.
[c] $K = 0{\cdot}0001$ m.

end of simulation. The root-mean-square error values (RMSE) between modelled and experimental results for all six canopy interception modelling approaches are summarized in Table VI. As the RMSE values indicate, the more mechanistic and detailed modified Merriam and van Dijk models predicted canopy interception depths closer to experimental results.

When comparing the simulation results of the modified Merriam canopy model and the van Dijk model with the experimental field results of Steiner *et al.* (1983) (study B), the von Hoyningen-Huene method for calculating $S^{c}_{\max}$ provided modelled results closer to those of the experimental results than the Brisson method, but not for van Dijk (Figure 3, Table VI). (Note: the von Hoyningen-Huene–van Dijk and Brisson–van Dijk lines overlap each other for most of the time period studied.) The best results for interception were observed with the von Hoyningen-Huene–modified Merriam model. The van Dijk model simulation produced interception values much lower than the experimentally measured values. Table VI indicates that the von Hoyningen-Huene–modified Merriam results for studies B1–B4 gave the best results overall compared with the other modelling approaches. Generally, the modified von Hoyningen-Huene–modified Merriam model produced results in closest agreement with the experimental results for canopy interception for both field studies.

The simulation results of the modified Merriam residue model (Equation (20)) and the CropSyst model (Equation (3)) were compared with the laboratory experimental results of Mohamoud and Ewing (1990) (study C). The modified Merriam results are in better agreement with the experimental results at the beginning of the rainfall simulation; CropSyst results are in better agreement at the end of the rainfall simulation (Figure 4). However, as summarized in Table VI, the modified Merriam residue interception model results were in good agreement with the other experimental results (C1–C3) and produced better temporal results than the CropSyst residue model.

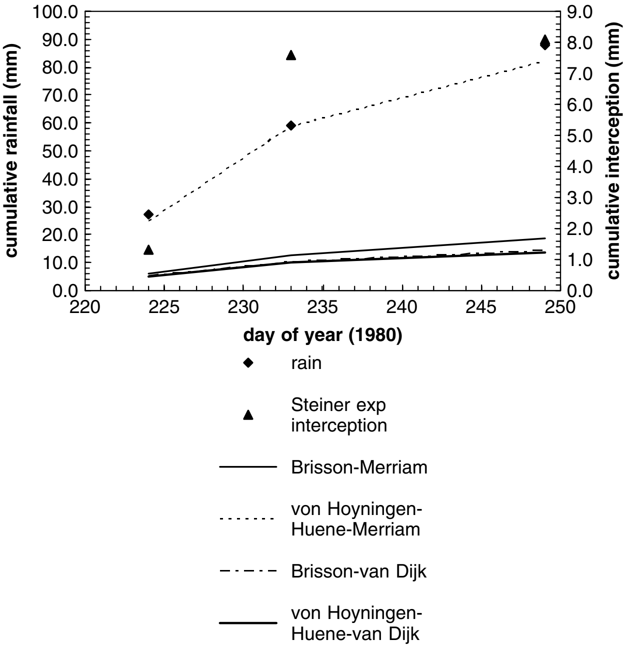

Figure 3. Cumulative rainfall, measured cumulative interception, von Hoyningen-Huene–Merriam modelled interception, and Brisson–Merriam modelled interception, von Hoyningen-Huene–van Dijk modeled interception, and Brisson–van Dijk modelled interception for plot B1 in the Steiner *et al.* (1983) study

Results of RZWQM study IA: canopy interception (sweetcorn)

The average effects of the no-interception scenarios versus canopy interception scenarios on cumulative amounts of canopy interception, net rainfall, runoff, infiltration, evaporation from soil and canopy, transpiration, and the change in soil water storage of 10 growing seasons are summarized in Figure 5a. Deep drainage was

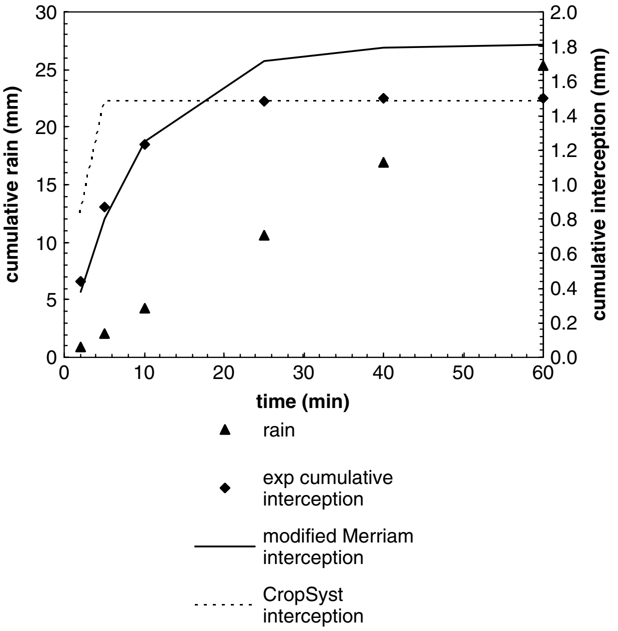

Figure 4. Modelled and experimental results of cumulative corn residue interception and cumulative rainfall for a rainfall rate of 25·4 mm h^{-1} from the Mohamoud and Ewing (1990) study (C1)

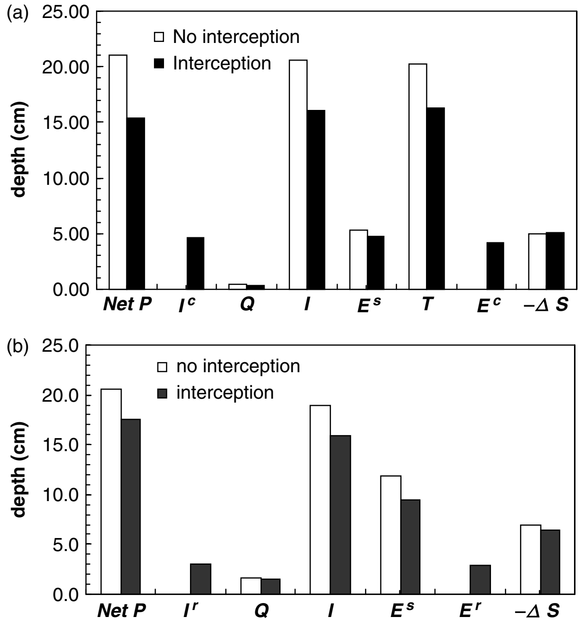

Figure 5. (a) Cumulative depths of water mass balance components (net precipitation Net P, canopy interception I^c, runoff Q, infiltration I, evaporation from soil E^s, transpiration T, evaporation from canopy E^c, and negative change in water storage $-\Delta S$ for (a) study 1A (canopy interception) and (b) study 1B, where I^c and E^c are replaced by 'r' for residue interception

minimal in both scenarios. As expected, canopy interception decreases runoff and infiltration, but also decreases the evaporation E^s and transpiration T from soil. As a result, although the water storage did decrease slightly more in the interception scenario, the change in soil water storage during the growing season is not significantly affected. The decreases in E^s and T resulted from lower infiltration and lower potential transpiration with interception; according to Equation (26a), the potential transpiration is reduced by canopy interception. This minimizes the difference between water storage values for the interception scenario compared with the scenario without interception. (Note, because ΔS is negative, it was graphically presented as $-\Delta S$ in order to have a positive value.) Additionally, total evapotranspiration ($ET^T = E^c + E^r + E^s + T$) in the interception scenario is higher than in the no-interception scenario (29·9 cm and 25·5 cm respectively). This is to be expected, as evaporation and transpiration from the soil are a function of the soil water availability and soil hydraulic properties; evaporation of intercepted water off the canopy, in this case (or residue), is readily available to meet calculated potential.

Results of RZWQM study IB: residue interception

The average effects of the no interception versus residue interception scenarios on the cumulative amounts of residue interception, net rainfall, runoff, infiltration, evaporation from soil and residue, transpiration, and the change in soil water storage of 10 seasons are summarized in Figure 5b. Deep drainage was negligible in both scenarios. Much like canopy interception, residue interception decreases runoff, infiltration, and evaporation, as well as the change in soil water storage. However, the difference in water storage between the interception (6·40 cm) and no-interception (6·99 cm) scenarios was relatively small. Again, the ET^T of the no-interception scenario is less than the interception scenario (11·9 cm and 12·5 cm respectively).

Results of RZWQM study II: canopy and residue interception (Akron, Colorado)

The effects of both canopy and residue interception and no interception on cumulative water balance components over 10 years of corn–fallow–wheat rotation are summarized in Figure 6. The yield and crop biomass during the crop seasons are given in Figure 7. Figure 6 shows essentially no difference in runoff, deep seepage, macropore flow, or the change in soil water storage between the interception and no-interception scenarios. The interception decreases infiltration to the same extent as it decreases E^s and T. Again the ET^T of the no-interception scenario is less than the interception scenario (383·8 cm and 386·2 cm respectively). Generally, LAI (not shown), yield, and crop biomass were lower for the interception scenario. The interception scenario invariably had lower transpiration, thereby reflecting the lower crop growth. Compared with the measured values in the field, the interception scenario was in slightly better agreement than the no-interception scenario (Figure 7). However, both scenario results were generally within the measurement error, and other simulation errors related to model structure and parameterization are probably greater than interception errors. On average, the reductions in yield, biomass, and LAI of the interception scenario, relative

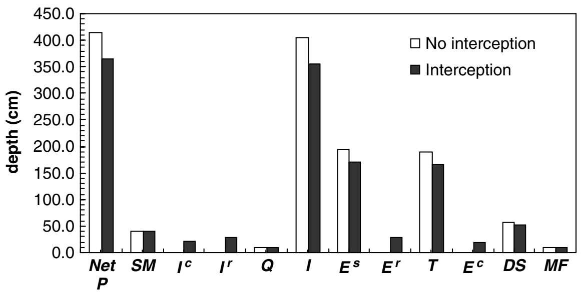

Figure 6. Cumulative depths of water mass balance components (net precipitation Net P, snowmelt SM, canopy interception I^c, residue interception I^r, runoff Q, infiltration I, evaporation from soil E^s, evaporation from residue E^r, transpiration T, evaporation from canopy E^c, deep seepage DS, and macropore flow MF) for the 10-year Akron study (study II)

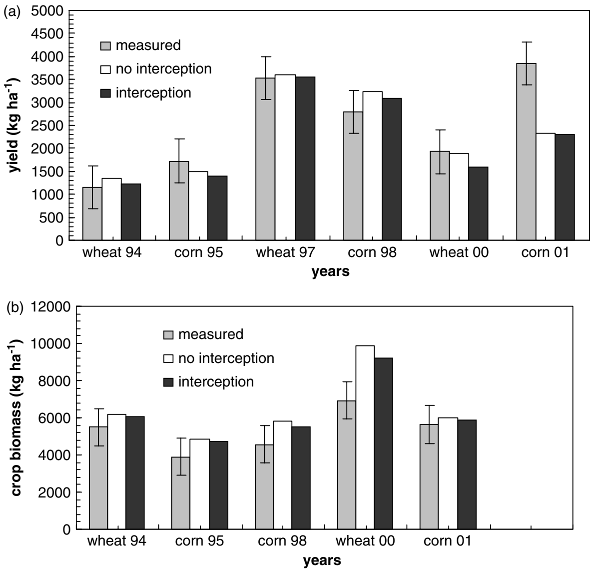

Figure 7. (a) Measured and simulated corn and wheat yields with and without interception during the 10-year Akron study (study II); (b) measured and simulated corn and wheat biomass with and without interception during the 10-year Akron study (study II)

to the no-interception scenario, were 6%, 19%, and 2% respectively.

The dynamics of the bromide tracer throughout the 10-year simulation for both the no-interception and interception scenarios were also examined. As observed from Figure 8a, the total mass of bromide in the soil is higher in the interception scenario than that of the no-interception scenario. This is attributed to the greater bromide seepage out of the bottom of the soil profile in the no-interception scenario (Figure 8b). The higher bromide deep seepage parallels the slightly higher water deep seepage summarized in Figure 6 for the no-interception scenario.

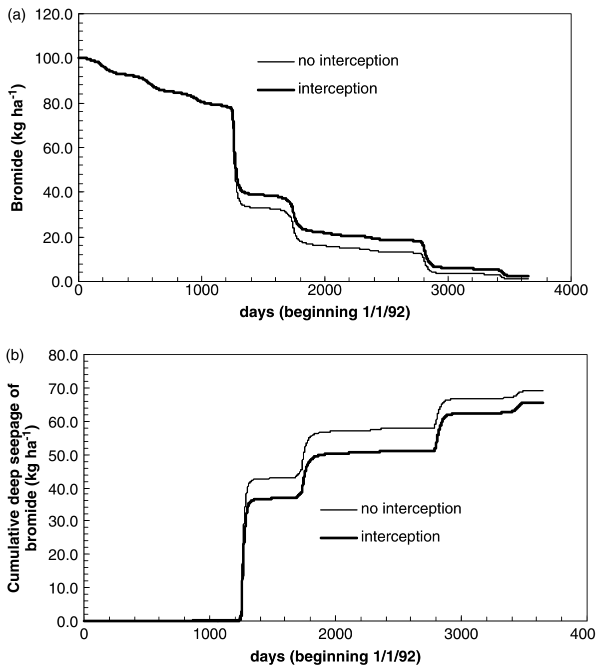

Figure 8. Temporal plots of (a) bromide tracer mass in the soil for the 10-year Akron study (study II) and (b) cumulative bromide seepage for the 10-year Akron study (study II)

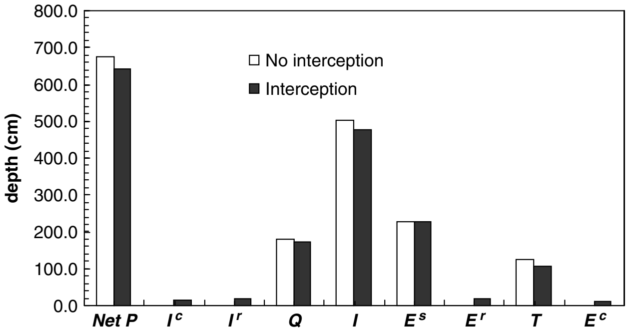

Figure 9. Cumulative depths of water mass balance components (net precipitation Net P, canopy interception I^c, residue interception I^r, runoff RO, infiltration I, evaporation from soil E^s, evaporation from residue E^r, transpiration T, evaporation from canopy E^c) for the 6-year theoretical Corvallis study (study III)

Results of RZWQM study III: canopy and residue interception (Corvallis, Oregon)

The effects of both canopy and residue interception and no-interception on cumulative amounts of water balance components over 6 years of a hypothetical corn–fallow–wheat rotation for the Corvallis, Oregon, study are summarized in Figure 9. Though not shown in Figure 9, there is essentially no difference in deep seepage or change in water storage between the interception and no-interception scenarios. There is a decrease in runoff, infiltration, evaporation, and transpiration with respect to the interception scenario. Again, the ET^T of the no-interception scenario is less than the interception scenario (351·6 cm and 364·5 cm respectively). As expected, the LAI and yield of both crops (Figure 10) were higher for the no-interception scenario due to the higher overall transpiration for the 6-year study. Though there was more canopy interception than in study II, a greater reduction in plant growth was not observed. On average, the LAI decreased by 3% and the yield decreased by 10% for the interception scenario.

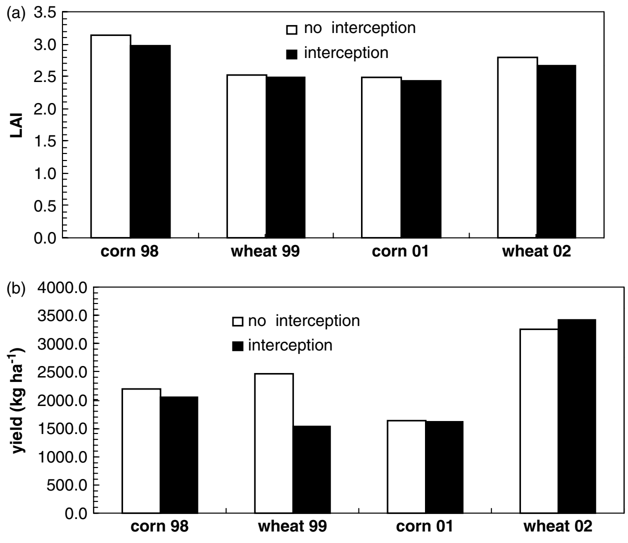

Figure 10. (a) Maximum seasonal LAI during the 6-year Corvallis theoretical study of canopy and residue interception (study III); (b) maximum seasonal yield during the 6-year Corvallis theoretical study of canopy and residue interception (study III)

SUMMARY

Canopy and residue interception of rainfall and irrigation by agricultural crops have long been overlooked in the hydrological cycle. Interception can readily affect the water and chemical balances in a soil system by altering the amount of water reaching the soil surface. Past studies have shown that crop canopies intercepted 22 to 58% of a given rainfall event, and crop residues intercepted a maximum of 29% for given rainfall events. The most significant factors concerning canopy interception are canopy cover, crop density, LAI, and rainfall or irrigation intensity and duration (Dunne and Leopold, 1978). Similarly, residue interception is a function of crop residue type, residue mass, residue cover, and rainfall or irrigation intensity and duration (Dingman, 1994). A model extended from the Merriam (1960) interception theory was developed for both residue and canopy for input in the RZWQM model. Evaporation of intercepted water by both reservoirs was developed from the Penman (1948) and Shuttleworth and Wallace (1985) theories. For simplicity, crop type, leaf geometry, leaf type, residue permeability, and wind are omitted from model development. The modified Merriam model for canopy and residue interception was tested against five current modelling approaches through comparison with the measured results of two field studies and one laboratory study. Overall, the modified Merriam model simulated results in closer agreement to the measured results than any of the other approaches did.

Upon validation and inclusion of the modified Merriam approach into the RZWQM model, three studies were performed to examine the quantitative effect of interception by canopy and residue on a number of water balance components, including cumulative amounts of canopy and residue interception, net rainfall, runoff, infiltration, evaporation from soil, transpiration, and the change in soil water storage. Based on the study results as shown in Figures 5–10, the presence of a canopy and residue in an agricultural system had a notable effect on the partitioning among water balance components. In general, interception of rainfall decreased soil evaporation, transpiration, infiltration, and runoff. Additionally, water storage decreased slightly due to canopy and rainfall interception. However, the relative decrease in water storage was small; less water infiltrated into the soil during interception, but less water was lost from the soil through transpiration and evaporation. Although changes in water content and profile storage were minimal, the simulated bromide leaching was shown to increase with no rainfall interception, as more water entered the soil in this scenario. Finally, the decrease in transpiration caused by canopy interception lowered LAI and average yield. With this new knowledge and ability to describe the model effects of residue and canopy interception quantitatively, the environmental impacts, such as chemical leaching and agricultural management (irrigation planning), can be examined and treated more effectively. The above findings (even if some of the effects were small) and the new interception models for crop canopies and crop residues are significant new contributions to knowledge for soil hydrologists.

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