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Experimental analysis of drainage and water storage of litter layers

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Leaf litter overlying forested floors are important for erosion control and slope stability, but also reduces pasture growth in silvopastoral systems. Little information exists regarding the value of percolation and storage capacity parameters for litter layers.

5 These estimates are needed for modelling better management practices for leaf litter. Therefore, this work measured the effect of four rainfall intensities: 9.8, 30.2, 40.4 and 70.9 mm h⁻¹ on the hydrological response of layers of three materials: recently senesced poplar leaves, fresh grass and woodchips. Maximum storage (C_{\max}), defined as the detention of water immediately before rainfall cessation, increased with
10 rainfall intensity. The magnitude of the increment was 0.2 mm between the lowest and highest rainfall intensities. Mean values of C_{\max} were: 1.27, 1.51, 1.67 and 1.65 mm for poplar leaves; 0.63, 0.77, 0.73 and 0.76 for fresh grass and; 1.64, 2.23, 2.21 and 2.16 for woodchips. Drainage parameters were: 9.9, 8.8 and 2.2 mm⁻¹ for poplar, grass and woodchips layers. An underlying soil matrix influenced the drainage flow from poplar
15 leaf layers producing pseudo-Hortonian overland flow, but this occurred only when the rainfall intensity was 40.4 and 70.9 mm h⁻¹ and accounted for 0.4 and 0.8% of total drainage. On the other hand, the presence of a poplar leaf layer had a damping effect on the drainage rate from the underlying soil matrix, particularly at intermediate rainfall intensities: 30.2 or 40.4 mm h⁻¹.

20 1 Introduction

Slope failures are complex natural phenomena that constitute a serious natural hazard in many countries. Among other factors, the stability of hill slopes is lost when the soil water pressure increases and the soil's shear strength is insufficient to resist downslope movement during periods of extended precipitation (Keim and Skaugset, 2003).

25 Poplar (*Populus* sp.) are commonly planted on moist, unstable hill slopes to prevent or reduce soil erosion while retaining the pastoral landuse (Wall et al., 1997). It is widely

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5 recognised that the reinforcing and binding effect of poplar roots and the reduction of soil moisture by evapotranspiration from the canopy are important for soil stability (Hathaway, 1973; Guevara-Escobar et al., 2000). Also, transpiration and rainfall interception from the canopy of these broad-leaf, deciduous trees is low in winter. During autumn, leaf litter laying on pasture is considered a problem in a poplar-pasture system because it reduces pasture growth and its tillering (Devkota et al., 1997; Guevara-Escobar et al., 2007). However, leaf litter cover is known to protect ground surfaces from raindrop impact and therefore, reduces soil erosion (Sato et al., 2004). This loss of momentum reduces the delivery rates of intense precipitation and releases stored water over time to the soil or the atmosphere. This smoothing of precipitation intensities by the leaf layer may translate into overall greater stability of hillslopes with widely spaced-planted poplar, as it is true for forest canopies (Keim and Skaugset, 2003). Guevara-Escobar et al. (2007) reported lower soil water content in the 0–150 mm soil stratum under widely spaced poplars relative to the open pasture during autumn-winter months, when the poplar were leafless. They attributed this fact to leaf litter interception, but this was unconfirmed.

10 Little information is available concerning the role of poplar leaf litter on the dynamics of rainfall interception, which is defined as the precipitation that is temporarily stored on vegetation and evaporates without reaching the ground. The mechanisms of rainfall interception depend on vegetation type, surface tension, mechanical activity as well as on the intensity and duration of rainfall (Zeng et al., 2000). A leaf litter layer has a capacity to store water on its surface, which is filled by rainfall and emptied by evaporation and drainage (Bussiere and Cellier, 1994; Gonzalez-Sosa et al., 1999). Litter mass determines water storage capacity, which is the most sensitive parameter for litter water dynamics (Tobon-Marin et al., 2000; Sato et al., 2004). Sato et al. (2004) showed that the broad-leaf litter of *Lithocarpus edulis* (Nakai) intercepted more rainwater than the needle-leaf litter of *Cryptomeria japonica* (D. Don). In a tropical rainforest, litter interception becomes more important hydrologically at lower rainfall intensities (Tobon-Marin et al., 2000). Leaf litter interception was reported to be as high as 8.9%.

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of annual rainfall in a native evergreen forest in Chile (Huber and Oyarzun, 1992). Balazs (1982) reported 18% rainfall interception by the litter of *Larix decidua* (Mill.) and 7% for *Fagus sylvatica* (L.) and *Abies alba* (Mill.). Consistent, but lower values (2–5% of annual rainfall) had been measured for *Populus tremuloides* (Michx.) forests in North America (Helvey and Patric, 1965). A key parameter in rainfall interception is the amount of precipitation temporarily stored on vegetation, which is termed water storage capacity (Helvey and Patric, 1965). However, field measurements are expensive, sometimes impractical and results are difficult to interpret due to variable meteorological conditions (Gerrits et al., 2007). An alternative is to use simulated rainfall to study water storage under controlled rainfall conditions (Putuhena and Cordery, 1996; Sato et al., 2004; Keim et al., 2006a). Determining the water storage of the leaf litter would be another guideline to the management of poplar plantings. In this article, the effect of rainfall intensity on storage dynamics is described for three types of material which could have a role as a soil cover to reduce erosion: poplar leaves, grass and coarse woodchips. These observations were compared with the estimates produced by the single-layer interception model proposed by Rutter et al. (1971), since the hydraulic mechanisms of the forest floor interception process are similar to the canopy interception process (Putuhena and Cordery, 1996).

The objectives of this work were to: obtain estimates of percolation and drainage parameters and storage capacity; assess the effect of a litter layer on the drainage rate of a underlying a soil matrix and assess the effect of litter mass and compaction from rainfall on the storage of the litter layer.

2 Material and methods

2.1 Rainfall simulator

A computer-controlled Norton ladder-type rainfall simulator was used to produce various rainfall intensities (Sutherland and Ziegler, 2006). This simulator oscillates at

varying speeds spraying a test area 2 m wide. A 5 m aluminium ladder was used to support a pipe manifold, pressure gauges, spray boxes and drive train. A rotary axle mounts four Veejet 80–100 nozzles spaced at 1.1 m. The ladder was 2 m above the soil surface. This arrangement hanged 2 m below from the roof beams of the laboratory.

5 The nozzles were supplied with water in sets of two; each set of nozzles had its own hose and pressure gauge. Each nozzle was enclosed in an aluminium spray box that regulates the spray for proper nozzle overlap and swath width. Each spray box had a window opening that could be electronically closed. The rotary axle positions the nozzles across the window whenever a signal was sent. A drain pipe collects excess
10 water from the spray boxes; that was when the window was closed or when the nozzle moved away from the window during the rotation. The rotation was not constant, so the nozzles rotated twice, stopped for a few seconds, and then rotated again. A clutch brake started and stopped the boom as regulated by a signal from the computer. A small gear motor (1/15 HP, 100 rpm) drove the rotary axle and the clutch brake. A 4 HP gasoline
15 provided water pressure of 47.6 kPa at the nozzles. A Qbasic program and a control box with a switch to turn on the oscillation axle simulated the selected rainfall intensity. Drop diameter was $1.8\text{ mm} \pm 0.2$ and the applied rainfall was constant with intensity. The spatial distribution of rainfall had a coefficient of variation of 14.4%. One sample container was positioned 2 m below each of the simulator's nozzles. This arrangement
20 allowed the rainfall to reach terminal velocity. The containers had a circular area of 0.26 m^2 and a height of 0.72 m. A nylon mesh (10 mm gap size) was used to hold the material samples inside the container. Outlets were fixed at the bottom of container to collect drainage. Simulated rainfall was applied using tap water.

2.2 Material

25 Three materials were tested: 1. woodchips (*Pinus* sp.), which are a sawmill by-product and can be used as mulching material after clear-cut to prevent soil erosion, it also served as a model of decomposed organic matter given their porous and loose structure that readily absorbs water; 2. fresh cut grass (*Aristida divaricata*, Humb. and

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Bonpl. ex Willd.), 0.2–0.3 m long, as a model of lodged tall grass and 3. recently senesced poplar leaves (*Populus nigra*, L.). Woodchips and poplar leaves were oven dried and then allowed to stabilize in the laboratory conditions. Fresh grass clippings were obtained every time from a nearby paddock. Average air dry bulk densities for these materials were 60, 48 and 15 kg m⁻³, their corresponding dry matter was 90, 25 and 85% respectively. Obtaining undisturbed samples was considered. However, enough random samples of the precise same mass or thickness was not feasible for the number of replicates needed. Mainly because the distribution of recently senesced poplar leaves in the field varies greatly from spot to spot and also wind plays a mayor role in its redistribution over time. Therefore, the present work was carried on with disturbed samples. Another reason for this was to reduce variability among samples and statistically identify small differences between the proposed treatments.

2.3 Test 1

For each material treatment, two layer thicknesses were tested: $z = 0.05$ and 0.10 m. The average fresh weight of the materials used with the $z = 0.05$ m treatment were: 3.85, 1.92 and 0.62 kg m⁻² for woodchips, grass and poplar leaves, respectively; the corresponding values for $z = 0.10$ m treatment were: 9.23, 5.77 and 0.92 kg m⁻². Four rainfall intensities were tested: 9.8, 30.2, 40.4 and 70.9 mm h⁻¹. Treatments were allocated as a randomised complete block design, with the nozzles being the blocks. All material layers were replaced after one hour of rain simulation. One container, with no material layer, was left as a control for every rain simulation to measure incident rainfall (P). Each material layer \times layer thickness \times rain intensity combination was replicated three times.

2.4 Test 2

In this test only the poplar leaves were used. Treatments were: three layer thicknesses $z = 0$, 0.05 and 0.10 m and the four rainfall intensities described in Test 1. In Test 2 the

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nylon mesh was overlaying a 300 mm layer of sieved, dried and compressed sewage sludge. The granular texture of this material allowed constant infiltration of water. Also, this material did not collapse when saturated and the pore size distribution was preserved. This kind of material was chosen because the soil matrix would not be replaced between simulation runs. The rest of the container was packed with sand (0.2 mm) under the sewage sludge and the leaf layers. Oven dry bulk densities of the packed media were 0.95 and 2.0 Mg m⁻³ for sewage sludge and sand. Runoff (*R*) was measured as the drainage from an outlet fixed at the interface between the material layer and the soil matrix. These outlets were adjustable in height and had a protecting screen to avoid the collection of incident rainfall. This runoff would correspond to rapid subsurface flow production through the leaf layer, sometimes called the “thatched roof effect” (Weiler and McDonnell, 2004) or pseudo-Hortonian overland flow, whereby differences in saturated hydraulic conductivity at the organic-mineral soil boundary create lateral flow in the near-surface horizon (Helvey and Patric, 1965; Brown et al., 1999). The soil matrix in each container was maintained near saturation. Prior to each simulation run, one hour-42 mm h⁻¹ rainfall was applied to the soil matrix in the containers until constant drainage was obtained. All leaf layers were replaced by fresh material after one hour of rain simulation.

2.5 Test 3

In this test, we used poplar leaves masses of 0.2, 0.4, 0.6, 0.8 and 1.0 kg m⁻² and applied a rainfall intensity of 30.2 mm h⁻¹. Three rain-drain cycles were obtained for each sample. Rain was applied for one hour, drainage was allowed for one hour, rainfall was applied again for one hour, drainage was allowed for two hours, rainfall was applied for one hour once more and then, allowed to drain. Treatments were allocated as a randomised complete block design, with the nozzles being the blocks. The experiment was replicated four times. The leaf layers were replaced after each replicate rain-drain cycle.

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2.6 Measurements

Measurements were made for initial and final layer mass using an electronic balance. The weight of the water detained by the nylon mesh was subtracted to correct the original data. Rainfall, temperature, relative humidity, wind speed and air pressure were measured using a WXT510 multi-sensor (Vaisala, Helsinki, Finland). This sensor was connected to a CR1000 datalogger (Campbell Scientific Ltd., Shepshed UK), averaging at a 1 min time step. The sensor measured rainfall with a resolution of 0.01 mm. Drainage was recorded during and after the rainfall simulation. Drainage was weighed every 5 min in Test 1 and 2. In Test 3 the drainage outlets were individually routed into tipping-bucket gauges and recorded once per minute. These TE-525LL-L (Texas Electronics Inc., Dallas TX) gauges were calibrated to record 0.254 mm per tip. The storage (C [mm]) was indirectly calculated as:

$$\frac{dC}{dt} = P - D - R. \quad (1)$$

where P (mm h^{-1}) was the amount of rainfall supplied from the simulator and D (mm h^{-1}) and R (mm h^{-1}) the amount of drainage collected from the outlets of each container. Two different interception storage capacities were determined for each sample: C_{\max} (mm), the maximum storage of the material layer calculated as the amount of water detained in the sample immediately before the rainfall simulation ceased; C_{\min} (mm), the minimum storage of the material layer calculated as the amount of water detained after free drainage had ceased (Putuhena and Cordery, 1996).

2.7 Estimation of model parameters

The elements of the litter layers do not form a connected network and cannot allow water movement by capillarity; movement of water only can take place by dripping of intercepted water and penetration of rainfall through gaps (Bussiere and Cellier, 1994). Therefore, the drainage process was modelled according to Rutter et al. (1971). The

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resulting predictions of drainage and storage were compared with the experimental data.

Briefly, the model considers the changes in water stored within the vegetation as determined by the balance between P , D and evaporation (E (mm h^{-1})) from the water stored within a vegetation compartment:

$$\frac{dC}{dt} = (1 - fg) \times P - k \times e^{b \times (\frac{C}{S})} - (E(\frac{C}{S})). \quad (2)$$

where t is time; fg is the ratio of rainfall that passes freely through the spaces of canopy vegetation (porosity).

The exponential term corresponds to the rain drained by the vegetation canopy (dripping or drainage), in which k and b are vegetation characteristic parameters, also known as percolation and drainage parameters. The S [mm] term corresponds to maximum storage of the reservoir and can be estimated by linear regression of the type:

$$T = b_0 \times P + b_1. \quad (3)$$

for $P > P_s$, where P_s is the amount of rainfall needed to reach saturation and T (mm h^{-1}) is throughfall (Rutter et al., 1971). The parameters b_0 and b_1 results in estimates of the ratio of evaporation to rainfall and S , respectively (Klaassen et al., 1998). Drainage was predicted using the relation between drainage and storage (Bussiere and Cellier, 1994):

$$D = k \times \exp(bC). \quad (4)$$

Evaporation was considered negligible, according to the environmental measurements made during the simulation runs and because the experiment was conducted in a laboratory environment and wind speed was zero. These conditions were chosen because the interception fraction and the storage capacity parameter are better identified when evaporation is low (Vrugt et al., 2003). The parameters k (mm s^{-1}) and b (mm^{-1}) were

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estimated independently from the tests described above. Data for this model was obtained using a layer thickness of $z=0.05$ m and a rainfall intensity of 70 mm h^{-1} . This rainfall rate satisfied $P \geq P_s$. Three materials were used: woodchips, poplar leaves and fresh grass. Three replicates were obtained for each treatment combination. The container used had a circular area of 0.1 m^2 , and its bottom had nylon mesh (10 mm gap size) to hold the material in place. The container was weighted constantly by an electronic balance. The container frame avoided the contact between the mesh and the balance plate. Drained water from the base of the material layer and the container weight were recorded every minute.

2.8 Statistical analysis

Data were analysed as a randomised block design using the general linear model procedure (GLM) of SAS (SAS Institute, Cary, NC, USA). Significance of all pre-planned comparisons was obtained using the Tukey test (Steel and Torrie, 1980). Models were fitted using the GLM procedure within SAS to establish the significance of regressions. The minimum level for significance was set at $p \leq 0.05$.

3 Results and discussion

3.1 Test 1

The materials tested differed in C_{\max} and C_{\min} (Fig. 1). Maximum storage increased with increasing rainfall intensity in the case of poplar leaves. This relation was not as evident for the fresh grass or woodchips. Differences in C_{\max} between the layer thicknesses were more evident for fresh grass. Small differences in C_{\max} between layer thicknesses were identified for woodchips and poplar leaves, but this did not occur for all rainfall intensities. The effect of rainfall intensity on C_{\min} was not very clear. Minimum storage of woodchips tended to decrease with increasing rainfall intensity.

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the case of poplar leaves and fresh grass, C_{\min} remained fairly constant with respect to rainfall intensity. Also, the effect of layer thickness on C_{\min} was not constant.

The water storage of poplar leaves and fresh grass layers after draining ranged from 0.4 to 0.7 mm, when expressed as the weighted mean storage per unit of dry mass. These values were lower than those reported previously: water storage after drainage of *Pinus radiata* slash was 0.7 mm (Kelliher et al., 1992); Putuhena and Cordery (1996) found that C_{\min} was 0.96 and 1.12 mm for coniferous and eucalyptus litter types; Tobon-Marin et al. (2000) for Amazonian rainforest litter reported 1.5 mm storage after drainage; the C_{\min} reported by Sato et al. (2004) for coniferous and broadleaved litter types were in the range of 0.27–3.05 mm and; measured C_{\min} of bracken litter was 1.67 mm (Pitman, 1989).

In this test the 9.2 mm h^{-1} rainfall intensity was not sufficient to saturate the woodchips layers and therefore, this simulation run was not considered in the results. The performed analysis of variance explained 97.6 and 99.3% of the variation of C_{\max} and C_{\min} due to the effects of layer thickness, material and rainfall intensity. This suggested that the experimental units and the conditions in the laboratory varied very little between simulation runs.

3.2 Test 2

In this test the objective was to evaluate pseudo-Hortonian overland flow and this occurred only when the rainfall intensity was 40.4 and 70.9 mm h^{-1} ; this accounted for 0.4 and 0.8% of drainage. Drainage flow originated from the bottom of the containers in Test 1 and 2 are presented here together because they show similar trends although there were some differences (Fig. 2, Fig. 3). In Test 1 there was no underlying soil matrix below the leaf layers and, approximately after 15 min, the drainage rate stabilized to maximum rates equivalent to the applied rainfall intensity. When the soil matrix and the leaf layer were considered in Test 2 (for poplar leaves only), the drainage rate stabilized after 20 to 40 min; depending on rainfall rate (Fig. 3). With the exception of the simulations involving the 9.2 mm h^{-1} treatment, drainage initiated almost instantaneously.

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neously in the absence of the leaf layer. This condition indicated that the soil matrix was very close to saturation.

The initial drainage rate for the poplar leaves in Fig. 2 was very similar regardless of layer thickness or rainfall intensity. In Fig. 3, the drainage rate was different between the two layer thicknesses evaluated (0.05 and 0.10 m). However, the combined effect of the leaf layer and the soil matrix must be considered. Drainage started earlier when a leaf layer was not present and drainage rate was initially higher when rainfall intensity was 30.2 or 40.4 mm h⁻¹ (Fig. 3b and c). Whereas when the rainfall intensity was low or high, the drainage rate was similar regardless of the layer thickness or the presence or absence of the leaf layer (Fig. 3 a and d). This suggested that the leaf layer had a higher effect on drainage at the intermediate rainfall intensities.

Considering the result of Test 2 when rainfall intensity was 9.2 mm h⁻¹ and a leaf layer was present, drainage was low during the first part of the experiment, but then increased to rates higher than 9.2 mm h⁻¹. This could indicate that C was higher than C_{\max} during the first 30 min and then rainwater was released at a higher rate later during the experiment. However, at the highest rainfall intensity of 70.9 mm h⁻¹ water flow was very fast and the leaf layer had little effect on reducing drainage. The results of Test 2 showed a damping effect of the poplar leaves layers at intermediate rainfall intensities. In particular, the $z=0.1$ m layer effectively stored water temporarily in comparison with the no layer treatment (Figs. 3b and c). Actually, drainage rate showed some spikes when the leaf layer was not present (Figs. 3a, b and d), suggesting a positive pore pressure within the soil matrix. However, their significance was difficult to interpret in the absence of pore pressure measurements within the soil matrix.

No difference was found for the values of total drainage between the Tests 1 and 2 ($p \leq 0.05$). Also, the values of C_{\max} obtained in Test 2 were similar to those obtained in Test 1 for the poplar leaves layers and the corresponding rainfall intensities. In Test 2 the values of C_{\max} were obtained as the difference by weight of the leaf layer when the rainfall simulation was stopped and the initial weight of the sample. Whereas in Test 1 C_{\max} was the result of the water mass balance (Eq. 1). This result suggested that the

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soil matrix had no effect on the final maximum storage of the leaf layer. However, the observed pseudo-Hortonian flow and the lower drainage rate during the first part of the experiment (at rates lower than 70.9 mm h^{-1}) suggest that further studies of the leaf layer-soil matrix interface must be researched to evaluate transient storage. Some authors indicate that the storage, when free drainage has ceased after rain (C_{\min}), is more important for moisture dynamics of the forest floor than C_{\max} because gravitational water is drained 30 min after the end of rainfall (Putuhena and Cordery, 1996; Sato et al., 2004). However, C close to C_{\max} , represents an amount of water that dampens and lags rainfall intensity and is dynamic in nature (Keim et al., 2006). In the present work, an increase of C_{\max} was related to rainfall intensity. Considering the case of poplar leaves and the rainfall intensities of 9.8 and 70.9 mm h^{-1} , the magnitude of the increments were 0.5 and 0.2 mm for layer thicknesses of 0.05 and 0.1 m . Keim et al. (2006a) examined branches of eight species and found that storage was 0.2 mm greater at rainfall intensity of 420 than at 20 mm h^{-1} .

Keim et al. (2006a) proposed that increased storage proportional to rainfall intensity results from the balance between the addition of water and the dislodging of the existing storage. Dominant forces that contribute to storage are gravity and cohesion. Sato et al. (2004) argued that water storage capacity of litter layers was proportional to the litter mass regardless of layer thickness; and this signified that the storage of the litter layer may not be determined by the “capillary water” held in the gaps created between litters, but by the “adhesion water” held by each litter surface. Results from Test 3 support this view. However, viscosity is another force that might influence water detention by some surfaces, particularly rough surfaces; i.e. those with a high ratio between the total surface area and the geometric surface area (termed roughness factor or rugosity).

3.3 Test 3

Figure 4 shows the scatter diagram of rainfall storage versus poplar leaf mass for rainfall intensity of 30.2 mm h^{-1} . These values correspond to the first rain-drain cycle. Data

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showed that storage increased with increasing leaf mass. The value of C_{\min} remained constant after three rain-drain cycles ($p \leq 0.05$). Although, the layers decreased in thickness (Fig. 5); no statistical difference between the simulation runs of the same sample were found for their mean value of storage. These results suggest that the compaction of the litter layer little effect on the value of C_{\min} . In Test 3 three consecutive rain simulation runs were carried on; each time C_{\max} and C_{\min} were measured but no statistical differences were found. Similar results were reported by Sato et al. (2004). This suggested that during the rain-drain cycle (7 h) recently senesced poplar leaves absorbed little water. Therefore, the values of C_{\min} obtained in this test were representative of the quantity required to wet all surfaces (Rutter et al., 1971). If the surface could absorb water between runs, then C_{\min} would be higher for each run until a steady state-weight was reached, as in the case reported by Pitman (1989). More fragmented materials (Pitman, 1989), as the woodchips tested in the present work, would have a higher absorption rate. Water absorption could explain the poor relationship between measured and modelled drainage and the overestimation of C shown in Fig. 6 for woodchips. In general, data showed that the relationship proposed by Rutter et al. (1971), between drainage and storage holds for poplar leaves and fairly for fresh grass.

Lateral movement of water only was observed when an underlying soil matrix was present. This finding disagrees with the work of Sato et al. (2004) of lateral movement of water within layers of broad-leaf litter of *L. edulis*. In that work a soil matrix was not used. It is possible that both, leaf shape and the soil matrix interface play a role in the spread of water laterally and a more uniform, wetting front of the litter surfaces. Nevertheless, the effect of lateral movement and leaf shapes on runoff in a slope still remains to be determined.

3.4 Estimation of model parameters

Three simulations using a 70 mm h^{-1} rainfall intensity were made for each material to obtain the relationship between D and C . However, only the data from the poplar leaves could be represented accurately by a single regression model. Therefore, a

regression model was fitted for each material simulation and the average values of b and k parameters were used (Table 1). Less accuracy in the predictions was expected for the grass and woodchip materials because the standard error of the mean was higher for the b parameter. Consequently, agreement between observed and modelled values of D was good only for the poplar leaves layers ($r^2=0.97$, Fig. 7). As an example, the time trends of observed and modelled C are presented using the data obtained in Test 1 for a rainfall intensity of 40.2 mm h^{-1} (Fig. 6). Figure 7 suggested that b and k were independent of rainfall intensity and layer thickness because these parameters efficiently modelled D from different layer thicknesses and rainfall intensities measured in Test 1.

3.5 Further research

This study showed that the amount of water stored by litter layers was important. For example, Guevara-Escobar et al. (2007) reported a 3.1 Mg ha^{-1} litter fall during the autumn months in a site with mature poplar planted at 37 stems per hectare in the Pohangina Valley, New Zealand. This amount of litter would have a C_{\min} of 0.6 mm (Fig. 4) and represent 60% of that from the poplar canopy in full leaf (Guevara-Escobar et al., 2000). However, the present experiments showed that the damping effect on drainage was higher when the litter mass was close to 1 kg m^{-2} (Test 1 and 2). Because silvopastoral plantings for soil erosion control advocate low stocking densities, then it would be likely that the storage of leaf litter to be in the range of 0.2–0.6 mm, assuming a uniform leaf litter distribution on the landscape. The redistribution and accumulation of leaf litter in depressions and drainage channels downslope or near poplar is another unexplored mechanism to reduce soil erosion. In this case leaf litter mass would be higher. As organic matter builds up from leaf litter, more water could be retained, decrease flow velocity and enhance water infiltration. Orndorff and Lang (1981) reported that microtopographic depressions influenced leaf redistribution; for example, the mass of leaf litter upslope from fallen logs was as much as eleven times greater than the average stand value for litter mass. Grazed hillslopes develop a distinctive microtopography with track

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and inter-track areas. Also animal treading, particularly from heavier animal classes, have a negative effect on the soil structure and reduces pasture growth (Tian et al., 2006). Nevertheless, track areas probably have a role in intercepting runoff (Nguyen et al., 1998) but also in the accumulation of leaf litter.

5 Analysis of landsliding caused by a rainstorm, superior to 200 mm in 24 h and with a return period of 150 years, in the Pohangina Valley showed that topography, geology and vegetation cover all had a strong influence on widespread landslides occurrence (Hancox and Wright, 2005a). Landslide density was 38 landslides km² in an area of 20 km² (Hancox and Wright, 2005b). Poplar and willow plantings appeared to have some influence on reducing landsliding as the landslide densities were lower (18‰) than for bare pasture (50‰), although higher than the 7‰ damaged area recorded for pine plantations or bush/scrub (Hancox and Wright, 2005a). Nevertheless, it must be considered that poplar and willow trees were also more often planted on very steep pasture slopes that were already vulnerable to landsliding. Hancox and Wright (2005b) reported that recently-milled areas with tree stumps in the ground were severely landslide-damaged and suggested that the forest canopy was more important in reducing landsliding than strengthening of soils by tree roots. Although pine slash from pruning has a storage capacity of 0.7 mm (Kelliher et al., 1992), the susceptibility of logged areas stresses the importance of the combined effects of roots, canopy and understory to reduce soil erosion. Vegetation provides different physical functions that help control soil erosion during rainfall events. Rainfall interception by the canopy is an important process widely studied. However, the mulching of the ground surface by leaf litter or the understory and their water storage has received less attention. The present work provided some insight of the effect of rainfall intensity, mass and materials on the drainage response. Models of soil erosion (e.g. Tian et al., 2006; Keim et al., 2006b) may be improved by explicit representation of the understory including the floor layers, because it can store amounts of water comparable to tree canopies and should have specific effects on intensity smoothing beyond those of the canopy (Keim and Skaugset, 2003). Further work should evaluate accumulation patterns of

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leaf litter, rainfall interception of grass-leaf litter complexes and hydrological connectivity occurring at the plot level.

4 Conclusions

This study confirms previous reports of increased maximum storage proportional to increased rainfall intensity. However, minimum storage remained constant with respect to increasing rainfall intensity. Lateral movement of water within litter layers and the effect of the soil matrix interface deserve further research. Drainage data from a near saturated soil matrix indicated that the presence of a poplar leaf layer dampens drainage rate, but total drainage was similar with or without a poplar leaf layer. This effect was related to rainfall intensity, at 9.2 and 70.9 mm h⁻¹ there was little influence on drainage but at intermediate intensities (30.2 and 40.4 mm h⁻¹, drainage rate was lower and lagged in time when compared to drainage from the soil matrix only.

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Table 1. Means for the parameters of the model $\ln(D)=k+bC$ to predict drainage.

Material	b mm^{-1}	SE^a	k^b mm s^{-1}	SE
Woodchips	2.15	0.13	0.00256	0.005
Grass	8.83	1.07	1.09265	1.689
Poplar leaves	9.92	0.20	0.69977	0.054

^a Standard error of the mean. ^b $\times 10^{-12}$.

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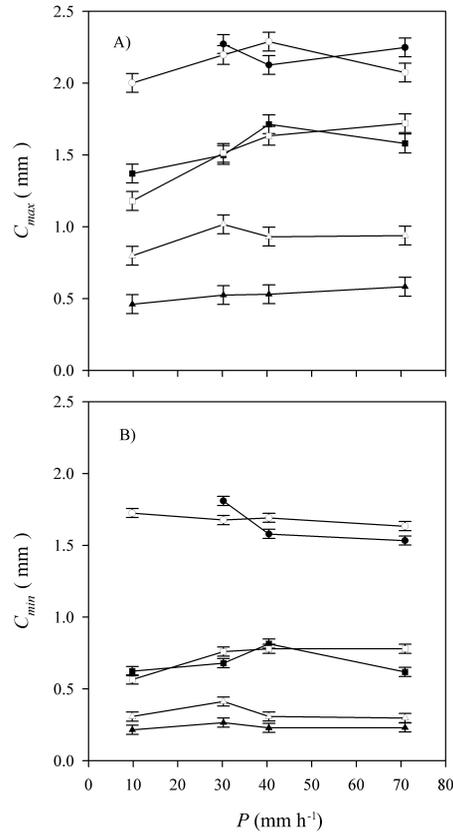


Fig. 1. Effect of rainfall (P) of various intensities on C_{\max} (A) and C_{\min} (B) of three materials (woodchips, circles; poplar leaves, squares and grass, triangles) and two layer thicknesses ($z = 0.05$ m, open symbols and $z = 0.10$ m, closed symbols). Data correspond to Test 1.

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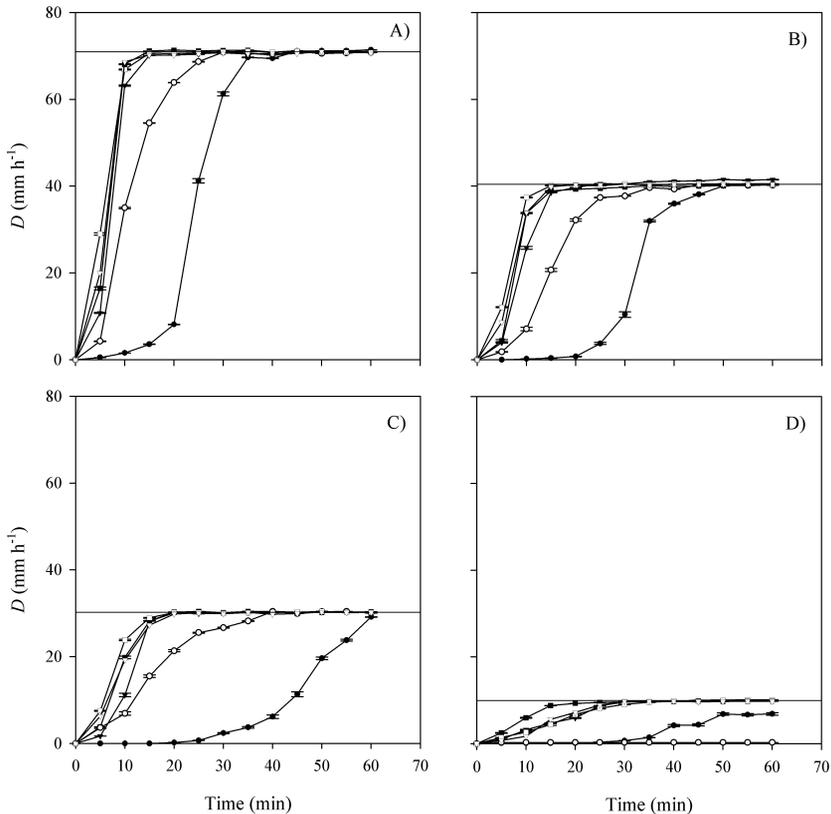


Fig. 2. Time trend of drainage (D) of three materials (woodchips, circles; poplar leaves, squares and grass, triangles) and two layer thicknesses ($z=0.05$ m, closed symbols and $z=0.10$ m, open symbols) under four rainfall intensities: **(A)** 9.8, **(B)** 30.2, **(C)** 40.4 and **(D)** 70.9 mm h^{-1} . Data correspond to Test 1. Vertical bars represent standard error of the mean.

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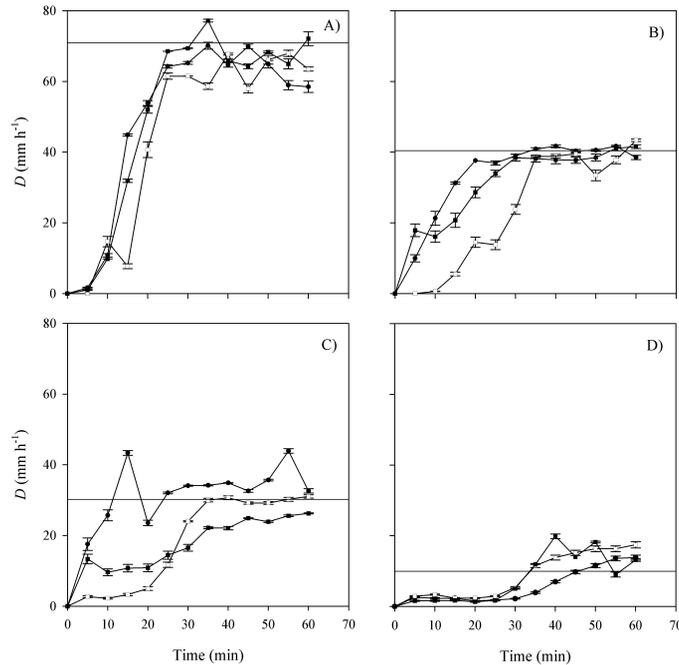


Fig. 3. Time trend of drainage (D) obtained in Test 2 for poplar leaves layer (squares) and an underlying soil matrix. Data corresponded to two layer thicknesses ($z = 0.05$ m, closed symbols and $z = 0.10$ m, open symbols) and four rainfall intensities (**A**) 9.8, (**B**) 30.2, (**C**) 40.4 and (**D**) 70.9 mm h⁻¹). The closed circles represent drainage from the soil matrix without a poplar leaf layer. Vertical bars represent standard error of the mean.

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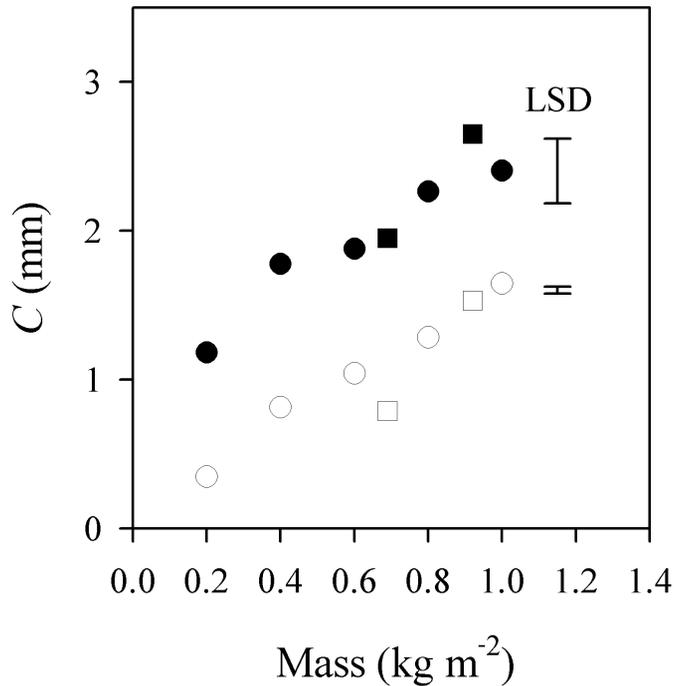


Fig. 4. Effect of layer mass on maximum storage (closed symbols) and minimum storage (open symbols) of poplar leaves. Circles and squares correspond to values obtained in Test 1 and 3 under a rainfall intensity of 30.2 mm h⁻¹. The least significant difference (LSD) corresponds to $p < 0.05$ and Tukey test.

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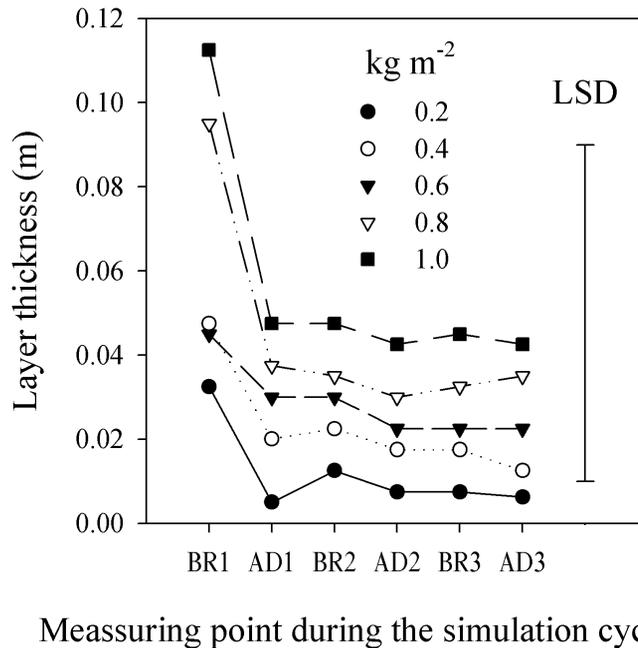


Fig. 5. Effect of litter mass on layer thicknesses at various points during the simulation cycle in Test 3: BR1, BR2 and B3, before rain started in simulation number 1, 2 and 3 respectively; AD1, AD2, AD3, after drainage in simulation number 1, 2 and 3. The least significant difference (LSD) corresponds to $p < 0.05$ and Tukey test.

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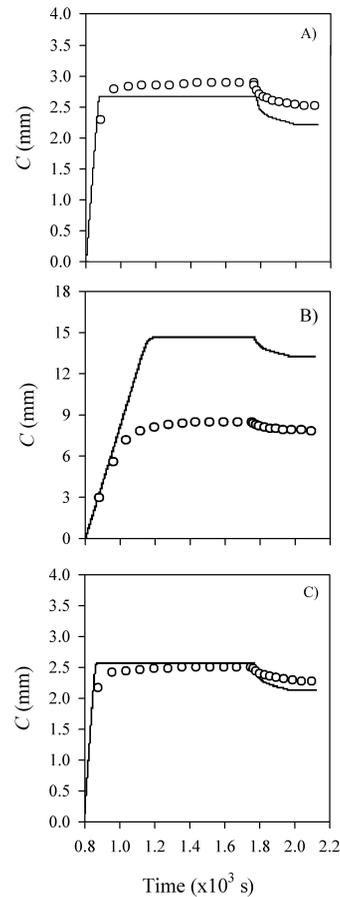


Fig. 6. Time trends of measured (open circles) and modelled (solid line) storage (C) of $z = 0.05$ m layers of fresh grass (A), woodchips (B) and poplar leaves (C) under a rainfall simulation of 40.2 mm h^{-1} .

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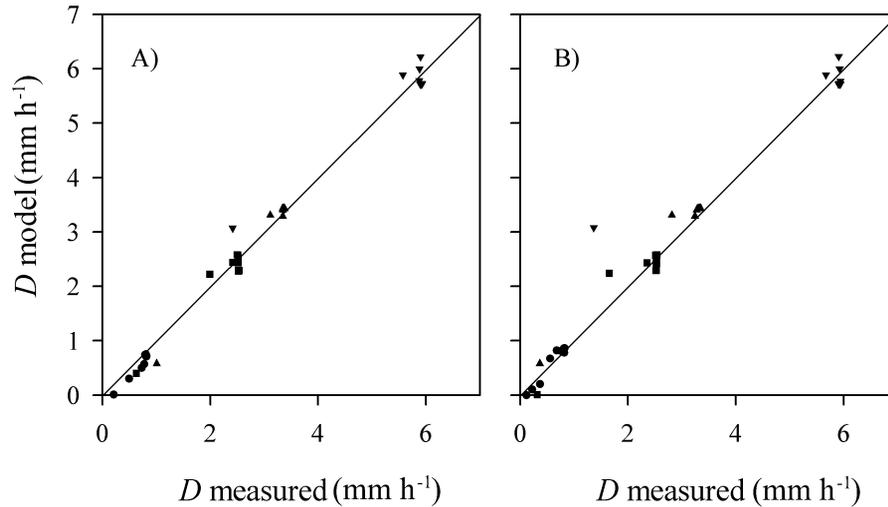


Fig. 7. Relationship between observed values of drainage (D_{measured}) and its estimates using the model $\ln(D) = k + bC$, (D_{model}). Data corresponds to poplar leaves and layer thicknesses of $z = 0.05 \text{ m}$ (A) and $z = 0.10 \text{ m}$ (B). Applied rainfall (P) of 9.8, 30.2, 40.4 and 70.9 mm h^{-1} are represented by circles, squares, triangles and inverted triangles, respectively.

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