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# **Capture of overland flow by a tree belt on a pastured hillslope in south-eastern Australia**

Running title: Capture of overland flow by a tree belt

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## **Abstract**

We describe a rainfall simulator experiment designed to measure the capture, by a fenced tree belt, of excess water generated as Hortonian flow from a pasture slope. Three rainfall events (48, 49 and 75 mm/h for 13, 30 and 30 min, respectively) were applied, of which 15%, 29% and 44%, respectively, ran off and drained onto the tree belt. The tree belt captured 100%, 32-68% and 0-28% of the runoff from the 3 events, respectively. These captured runoff volumes represented 31-39%, 22-45% and 0-29% increases in water supply to the trees, in addition to incident rainfall. Infiltration rates within the tree belt were up to 46% higher than in the pasture zone. This higher infiltration was mainly attributed to better soil surface conditions in the absence of stock and a 50-mm layer of tree litter. Overland flows within the tree belt formed tree litter into microterraces, which spread and slowed flows and allowed greater time for infiltration.

*Keywords:* runoff agroforestry, surface water management, tree litter, microterraces, infiltration, source-sink

## **Introduction**

In the semiarid agricultural regions of the world, there is growing interest in the placement of tree belts on hillslopes within run-on zones to increase their growth by increasing local water supply (e.g. by 'runoff agroforestry'; Dropplemann and Berliner, 2003; Abdelkdair and Schultz, 2005). Such tree belts also reduce hillslope water yield and hence reduce off-site waterlogging or dryland salinisation (e.g. McJannet *et al.* 2000 and 2001; Stirzaker *et al.*, 2002; Turner and Ward 2002).

The success of either endeavour requires that water moving downslope as runoff [overland flow, sub surface lateral flow (SLF) or both] is captured and used by the tree belt. Runoff water harvesting for agricultural production has been practiced for millennia by small farmers (Myers, 1975; Carter and Miller, 1991; Yair, 1983). Typically, this practice involves the manipulation of upslope catchment areas to shed water as Hortonian flow (overland flow resulting from infiltration excess). This overland flow is directed to the root zone of crops and trees via small earth structures where lower slopes and higher infiltration rates enhance the capture of overland flow and its storage in the soil profile. These imposed systems mimic some of the hydrologic characteristics of naturally 'patchy' or 'banded' vegetation systems described by Tongway *et al.* (2001). Most reported 'runoff agroforestry' is confined to arid regions of North Africa and the Middle East on small labour-intensive farm enterprises (Dropplemann and Berliner, 2003; Abdelkdair and Schultz, 2005). However, most reported scientific interest in the use of agroforestry for managing waterlogging and dryland salinity has emanated from southern

Australia and has focussed on the interception of SLF or deep drainage (e.g. (Lefroy and Stirzaker, 1999); Turner and Ward 2002; Ellis *et al.*, 2005a).

In Australia, land clearing for agriculture in winter-dominated rainfall environments has increased deep drainage and remobilised ancient regolith salt stores (Allison *et al.*, 1990); (Barnett, 1989). Hillslope agroforestry has been proposed to intercept and use excess water before it moves lower in the landscape to cause waterlogging or dryland salinisation. However, the success of tree belts on hillslopes in intercepting SLF in southern Australia is unclear. (White *et al.*, 2002) reported that a tree belt, growing on a duplex soil in Western Australia, used SLF equal to an additional 33% of rainfall. During a drought period, Ticehurst (2004) measured SLF of <1% of rainfall arriving at a tree belt planted at the break of slope (BOS) at Holbrook, New South Wales. McJannet *et al.* (2000; 2001) describe a detailed hydrologic study, on a BOS tree belt near Benalla, Victoria, which failed to show that SLF occurred, or was likely to occur, at their site.

There is very little information reported on the generation of overland flow upslope of tree belts. Silberstein *et al.* (2002) provide a 'ready reckoner' method, based on simulation modelling output, to estimate the combinations of slope and hydraulic conductivity likely to result in significant SLF. There is also little known about the ability of tree belts to capture and use excess water arriving as overland flow. The redistribution of overland flow, and associated nutrients carried in suspended sediments, is fundamental to the ecology and productivity of naturally patchy and banded semiarid vegetation systems (Noy-Meir 1973; Nulsen *et al.*, 1986; Ludwig and Tongway, 1995). It has been proposed that the resilience and diversity of agricultural systems could benefit from mimicking these characteristics (e.g. Hobbs and O'Connor, 1999).

Two fundamental questions about runoff agroforestry have not been answered: 1) which agricultural landscapes have overland flow as an important process, and 2) what is the capacity for tree belts to capture overland flow? Recently, Ellis *et al.*, (2005b) provided a surface water yield model for hillslopes designed as multiple banded agricultural systems, including runoff agroforestry systems. The water yield model contained two significant assumptions: 1) overland flow occurred only as saturation excess, and 2) capture of overland flow by the tree belt was only limited by maximum soil water storage and not by soil infiltration characteristics. Ellis *et al.* (2005b) showed reasonable agreement between the model and observations from naturally-banded mulga (*Acacia aneura*) systems. However, assumption (1) may not apply to most agricultural lands where infiltration is likely to be limited by the formation of a soil crust (Morin and Benyamini, 1977), and assumption (2) is largely untested.

In this study, we extend previous hillslope tree belt hydrology studies (White *et al.* 2002; McJannet *et al.* 2000; 2001; Ticehurst (2004) by testing the above two assumptions made by Ellis *et al.* (2005b). We describe a large scale (600 m<sup>2</sup>) rainfall simulator experiment designed to measure overland flow following three rainfall events applied to a pasture slope and tree belt sequence. In this experiment, the performance of the tree belt as a sediment trap was also evaluated, but these findings are reported by Leguédouis *et al.* (2005).

## Experimental methods

The experimental site was located in a pasture with a 6° slope on a farm near Boroowa (34°22'S 148°42'E), New South Wales, Australia. The site was a 28 m slope length of grazed perennial pasture draining onto a 12 m wide, 3 row tree belt. The 15 year-old *Acacia* spp. and *Callistemon* spp. tree belt was direct-seeded by the landholder for stock shelter and for biodiversity habitat. The trees were about 7.5 m high and the belt was aligned along the contour, with a greater canopy density near its uphill edge. Stock were excluded from the tree belt by a fence located near the drip line of the present canopy, although there was kangaroo dung present, indicating that wild animals had access. The soil was a red duplex (Chromic Luvisol; Driessen *et al.*, 2001 or Red Chromosol; Isbell, 2002) and dry bulk density increased with depth from 1.35 to 1.75 x 10<sup>3</sup> kg/m<sup>3</sup> (Erreur : source de la référence non trouvée). A mostly bare soil area associated with tree-pasture competition and stock traffic extended about 3.5 m beyond the fence line and into the pasture. A shallow compacted, non-hydrophobic, physical soil crust 5 - 15 mm deep covered most of the bare soil zone.

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An experimental area (length 40 m; width 15 m) was chosen in which slope, soil condition, pasture cover and tree cover were uniform. This area was divided into three plots to allow separate measurement of runoff from pasture (plot I), tree belt (plot III) and combined pasture-tree belt (plot II) (*viz.*, pasture draining into the tree belt; Erreur : source de la référence non trouvée and Erreur : source de la référence non trouvée). Plot



edges were formed by slotting steel sheeting into the soil and sealing at soil level with petroleum jelly (Erreur : source de la référence non trouvée). For each plot, steel channels were used to direct overland flow into a portable 'RBC' flume (Bos *et al.*, 1991). Flow depth  $h$  (mm) in the flumes was measured every three minutes using the 'dipstick method' and flows were calculated from known rating curves (Bos *et al.*, 1991). Spatial and temporal changes in overland flow patterns and associated changes in surface microtopography were recorded for all events.

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The experiment was undertaken shortly after mid-winter during a period of drought. Two weeks before the experiment, the pasture was heavily grazed for several days as part of the farmer's normal practices. Light rain had fallen during the interim, the soil was therefore moist and the perennial grasses were recovering from grazing. Clover (*Trifolium*) and medic (*Medicago*) pasture species had begun to germinate and total plant cover was about 50%. About 50% of the soil patches between plants were covered with pasture residue. Within the tree belt, the soil surface was mostly covered with tree litter (up to 50 mm deep), with smaller amounts of perennial grass, moss and other biological crusts (Eldridge, 2001). There was evidence of significant burrowing of worms and arthropods in the pasture but very few macropores were visible in the compacted soil immediately upslope from the fence line. However, the tree belt soil contained large (5 to 10 mm diameter) macro pores, mostly beneath the tree litter within the first 1 to 2 m of the tree belt where litter depth was greatest. The tree litter was beginning to be incorporated with to the soil surface by decomposition and the actions soil fauna.

Three simulated rainfall events (48, 49 and 75 mm/h for 13, 30 and 30 min) were applied uniformly across all three plots under windless conditions (Table 1). These events represented storms with return periods of 2, 10 and 50 year, for the local area, but time constraints required that they were applied sequentially within 30 min of each other. Simulated rainfall was delivered from 20 emitters with 15 positioned 5 m above ground level in the pasture and bare soil area and 5 positioned 1 m above the tree crowns. Water pressure was measured and adjusted to produce the desired rainfall intensities. The construction of the rainfall simulator used in this experiment is described in Motha *et al.* (2002) and Wilson (1999). Rain gauges (24 on the pasture, 12 under the trees) were spread evenly throughout the plots. After each rainfall simulation event, gauges were observed to determine uniformity of rainfall and mean rainfall depth for each event and plot. No attempt was made to measure canopy interception storage or loss because Dunin *et al.* (1988) reported canopy storage capacity and maximum interception loss in eucalypt forest to be only 0.35 mm and 1.0 mm/h respectively. These values are negligible when compared with our applied rainfall (Table 1). Immediately before the experiment, 3 replicate soil samples (0 - 75 mm depth) were collected from 9 positions down the slope, just outside the plot, for determination of surface antecedent water contents.

Rainfall and runoff volumes were calculated as:

$$P_i = A_i d_j, (i = I, II, III; j = 1, 2, 3) \quad (1)$$

$$V_i = \int_0^t Q_{ij} dt \quad (2)$$

where  $P_i$  = rainfall volume (L) falling on plot  $i$  of area  $A_i$  ( $m^2$ ),  $d_j$  = depth (mm) of rainfall event  $j$ ,  $V_i$  is runoff volume (L) from plot  $i$ ,  $Q_i$  is the runoff rate (L/s) from plot  $i$  and  $t$  is the duration (s) of the runoff event.

Assuming the 2 pasture-tree sequences were identical, and infiltration rates for plot III and the tree component of plot II were equal, then it can be shown that  $C_v$ , the volume of pasture runoff captured by the tree belt in addition to rainfall, can be estimated as

$$C_v = V_I - V_{II} + V_{III} \quad (3)$$

which can be expressed as a depth (mm)  $C_D$

$$C_D = \frac{V_I + V_{III} - V_{II}}{A_T} \quad (4)$$

where  $A_T$  is the area ( $m^2$ ) of the tree component of plot II.

Where hydrographs indicated steady state conditions (i.e. average  $\frac{dQ}{dt} = 0$ ), and field observations confirmed the whole plot area was contributing to overland flow for a period before rainfall cessation, steady state infiltration rates  $I_{SS}$  (mm/h) were calculated by considering mass balance during that period. i.e.  $I_{SS}$  was equal to rainfall rate, plus run-on rate minus runoff rate.

Steady state flow depth was also estimated from mass balance: the volume of water stored above the soil surface, at the time of the cessation of the rain, minus the infiltration volume, is the volume that flows of the plot. This gives an average depth  $\bar{D}_c$  (mm) when this volume is divided by plot area (m).

Manning's flow equation was rearranged to estimate the hydraulic roughness  $n$ , using  $\bar{D}_c$  to approximate hydraulic radius

$$n = \frac{\bar{D}_c^{2/3} s^{1/2}}{\bar{v}} \quad (5)$$

where  $s$  is slope and average flow velocity  $\bar{v}$  (m/s) was approximated as

$$\bar{v} = \frac{Q_{out}}{\bar{D}_c w} \quad (6)$$

where  $w$  was the width of overland flow (m), which spanned the entire width of the plot for the second and third events.

Following the experiment, soil bulk density profiles were determined from three replicate samples from each of seven depths with sample mid-points 37, 87, 200, 300, 400, 500 and 600 mm deep. Samples were extracted using thin-walled brass tubing (Mackenzie *et al.*, 2002) but dry, high strength soil prevented sample extraction from 600 mm deep in the tree belt. Bulk density profiles were measured at one position within each of the pasture and tree belt component of plot II. Total soil water stored  $S$  (mm) to a depth of 600 mm (200 mm below the greatest wetting depth observed) was calculated from 3 replicate hand auger samples from the same depths as the bulk density samples, 8 positions down the slope inside plot II. Time and resources did not permit replication at each position and soil water measurements were not used for water balance calculations as runoff measurements were adequate. Soil water conditions 'before' the experiment were represented using samples taken from outside the plot following the experiment to avoid disturbance of the soil surface before the experiment.

Three methods of error analysis were applied: 1) the rainfall error was expressed as the largest percent difference between  $P$ , for each plot, and  $P$  averaged within the whole pasture area; 2) where replicated soil measurements were taken, standard deviations were calculated; and 3) for non-replicated runoff, storage, capture and other flow characteristics, individual absolute measurement errors were estimated and accumulated during calculations. The measurement errors associated with time and plot area were considered small (<1%) and were ignored. The greatest error was  $\delta h$ , which occurred during the measurement of flow depth  $h$  (mm) in the flumes. Bos *et al.* (1991) estimate  $\delta h$  to be 1 mm when using a hardwood dipstick in the stilling well of the RBC flume. However, stilling wells were not installed and we measured  $h$  directly within the flow upstream of the flume sill using a steel rule aligned with the water flow to minimise errors from disturbing the water surface. We subsequently estimated  $\delta h = 2$  mm, plus a 2% error associated with uncertainty of the flume dimensions (Bos *et al.*, 1991), and used this estimate to calculate  $\delta Q$  and, hence,  $\delta V$ . For example,  $\delta C_D$  was determined as the addition of each  $\delta V$  associated with each of the three terms in the numerator of Eq. 4. This method calculated the largest likely measurement errors.

## Results

Antecedent water content of the surface soil (Erreur : source de la référence non trouvée) before the experiment was greatest in the pasture zone, decreasing towards a minimum at the interface between the tree belt and pasture (where tree leaf area was most dense), and increasing slightly within the tree belt. This was consistent with an expectation that the tree belt was the greater water user, and that the bare soil zone was likely to shed water. Although these measurements were made outside the experimental plots, they were considered to be reasonably representative of conditions inside the plots.

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During the first rainfall event (48 mm/h; 13 min) overland flow from the bare soil zone of plot I commenced at  $t = 1.5$  min and had fully spanned the width of the plot by  $t = 4$  min (Erreur : source de la référence non trouvée). Overland flow began to develop in the pasture at  $t = 8$  min. In plot II, overland flow from the bare soil and pasture components followed roughly the same temporal pattern as Plot I. Overland flow began to enter the tree component at  $t = 8$  min following the formation of a backwater (ponded water, upstream of flow obstruction) at the interface of the bare soil and the tree litter zones (Erreur : source de la référence non trouvée).

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The bare soil zone continued to generate most of the overland flow and steady state conditions were not reached in the pasture areas during this first event. As overland flow

from the bare soil and pasture components of plot II moved further into the belt, tree litter formed microterraces (up to 25 mm high and approximately 100 mm apart; ).

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These microterraces slowed and spread the flow, which was visually estimated to cover about 40% of the tree belt component area of plot II. For this first event, runoff from the bare soil and pasture in plot II was insufficient to ‘break through’ the tree belt component and was completely (100%) captured.  $\Delta S$  in the tree belt was calculated to be greater than rainfall depth and represented a  $35 \pm 4\%$  increase in water supply to the trees, in addition to rainfall (Table 1). Although small amounts (maximum  $< 5\%$  of the area) of local ponding occurred in plot III, no runoff was measured from this event.

PLEASE INSERT Table 1 ABOUT HERE

The second rainfall event (49 mm/h; 30 min) generated considerable overland flow from the bare soil of plot I (Erreur : source de la référence non trouvée), commencing at  $t = 1.3$  min. Runoff from the bare soil and pasture of plot II, plus rainfall, exceeded the infiltration capacity of the tree belt component so that runoff was generated from the whole plot II sequence.

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Runoff at the exit of plot II commenced just after  $t = 12$  min, almost simultaneously with runoff commencing from plot III. Steady state was reached on plot I at  $t = 20$  and was approached on plot III after 28 min. During the second event, a backwater also formed immediately upslope of the tree belt component of plot II and within the tree belt,

microterracing slowed and spread the flow. Some concentrated flow paths formed within the tree belt and began to overtop and breakout in small sections (up to 150 mm wide) of the microterraces. However, the microterraces generally remained intact and flow paths were slowed and convoluted over approximately 95% of the tree belt area within plot II and overland flow spanned the full width of the plot. Flow depth was estimated visually to be about 15 mm in the concentrated flow paths and up to 5 mm in more diffuse areas. During the second event,  $\Delta S$  in the tree belt component of plot II was again greater than rainfall depth (including measurement errors) so that  $50 \pm 18\%$  of the overland flow was captured by the tree belt. This represented a  $33 \pm 12\%$  increase in water supply to the trees, in addition to rainfall (Table 1). In plot III, tree litter also formed microterraces and flow depths were quite variable, but typically much less than in the tree component of plot II.

The third rainfall event (75 mm/h; 30 min) generated overland flow more rapidly (Erreur : source de la référence non trouvée), commencing at about  $t = 0.5$  min in plot I where water ponded to depths  $> 1.5$  mm and flows had a slow and convoluted runoff pattern. Runoff from upslope began entering the tree component of plot II at  $t = 1.2$  min.

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Flow depth in the tree component of plot II increased rapidly and reached 5 to 10 mm over most of the plot, about 20 mm in the concentrated flow paths and began to exit plot II at  $t = 9$  min. Steady state was reached in plots I and II at  $t = 13$ , and 15 min, respectively, although the variable structure of the microterraces produced 10 to 15% variations in flow rate in plot II. Again, during the third event, plant litter microterraces



retained their structural integrity over the vast majority of the tree belt component and overland flow spanned the whole width of the plot. For this event,  $\Delta S$  in the tree belt was similar to rainfall depth (within the bounds of measurement errors) and we therefore estimated capture from this event was zero, but could have been as high as 28% when measurement errors were considered (Table 1). Runoff in plot III commenced almost simultaneously with plot II (Erreur : source de la référence non trouvée) but did not peak until about  $t = 20$  min, reaching a maximum flow depth of about 10 mm because flows were constrained by the microterraces of tree litter.

Flow measurements allowed calculations of steady state infiltration  $I_{ss}$  on plot I and plot III for the second and third rainfall events and on plot II for the third event only. Combinations of these values allowed two checks for the hydrologic similarity of the two longitudinal sequences of the experimental site, a critical assumption of Eq. 3. First, because steady state was reached in both plot I and plot II during the third event, this allowed an additional mass balance check of  $I_{ss} = 53.8$  mm/h for the tree component of plot II. This value was similar to 45.3 and 50.4 mm/h from the tree plot III (Table 2) and is within the range of the largest measurement errors. Second, an areal average of  $I_{ss} = 40.7$  mm/h from plot I and plot III for the third event and is similar to the 41.9 mm/h measured from plot II (Table 2) and also within the range of measurement errors.

PLEASE INSERT Table 2 ABOUT HERE

After the experiment, the depth of soil wetting from the 3 applied rainfall events was 200 - 300 mm in the pasture zone, <50 mm in the bare soil zone, and 100 - 300 mm in the tree belt. Stored soil water ( $S$ ) after the experiment, was much greater than before the

experiment, where 'before' is represented by samples taken outside the experimental plots (Erreur : source de la référence non trouvée). These values are only indicative because of lack of spatial replication. Immediately after the experiment and one day later, soil profiles were exposed within the pasture, the bare soil zone, the tree belt and at the lower end of plot II, however, no SLR (sub-surface lateral flow) was observed.

## **Discussion and conclusions**

Field observations, soil water measurements and rigorous rainfall and runoff measurements showed that that runoff generated from upslope pasture and the bare soil zones can be captured by a tree belt lower on the slope. These findings support the conceptual source-sink model for a hillslope pasture-tree belt sequence (Ellis *et al.*, 2005b). However, at our experimental site, we found the 2 assumptions made by Ellis *et al.* (2005b) to be invalid. First, field observations showed that overland flow was generated as infiltration excess (Hortonian flow) and not by saturation excess, although this would not be true for all soil types. Second, the capture of overland flow was limited by soil infiltration rate, and not by maximum soil water storage. Ellis *et al.* (2005b) also used indirect measurements of soil surface condition (Tongway and Hindley, 2004) to suggest that significantly greater infiltration rates could be expected within non-grazed tree belts, compared to pasture. Our experiment has confirmed this and demonstrated that  $I_{SS}$  in the tree belt was up to 46% higher than  $I_{SS}$  in the pasture. Moreover, the tree belt captured 100%, 32-68%, 0-28% of the runoff from the pasture, resulting from 1 in 2-year, 1 in 10-year and 1 in 50-year storms, respectively, in addition to rainfall (Table 1). It is likely that these values were affected by the sequence of the applied events, in particular, the pre-wetting from the preceding event. Even so, the captured water represented significant additions to the incident rainfall from the 3 events, respectively, 31-39%, 22-45% and 0-29%. These values could have significant implications for the productivity of tree crops in dry areas.

Compared to the pasture, the greater infiltration of water within the tree belt was mainly attributable to four physical characteristics: 1) the presence of tree litter; 2) initially drier soil; 3) the greater abundance of large (< 5mm diameter) macro pores open to the surface; and 4) the absence of a compacted soil crust. Field observations plus  $\bar{D}_c$ ,  $\bar{v}$  and  $n$  calculations confirmed that the slowing and spreading of overland flow by microterraces of tree litter provided a longer period for infiltration to occur (). Drier soil may also present greater opportunity for infiltration and storage, but alone does not guarantee it. Significant volumes of overland flow passed over the bare soil zone and into the tree belt, and a 1 to 2 m backwater formed on this zone during each event. However, only a very small amount of this water infiltrated the bare soil, as indicated by a very shallow (< 50 mm) depth of observed wetting and change in  $S$  (Erreur : source de la référence non trouvée).

While selected macro pores were observed before and after the experiment, their role in the greater infiltration capacity of the tree belt is only postulated. However, it is likely that that they could have conducted significant amounts of water where water was ponded and the soil surface was saturated. Time did not allow a comprehensive assessment of large bio-pores as this is a lengthy and destructive process, and it is not known what proportion of them were open to the soil surface. However, Lavelle (1997) discusses how soil macro-fauna function as 'system engineers' [see also Lavelle and Spain (2001, p346)].

The compacted soil crust in the bare soil zone played a significant role in generating overland flow and minimising local infiltration. Therefore, we can safely assume that the

absence of this crust within the tree belt improved infiltration. Biological crusts, however, can serve as pioneer species to begin the process of improved surface structure and surface roughening by accumulating litter (Belnap and Lange, 2001). The absence of a compact soil crust, the presence and the partial incorporation of tree litter ('joining' the litter layer to the soil surface), greater biological activity and the greater infiltration capacity of the tree belt appear to all be interrelated. This is consistent with the ecological processes reported to occur in 'patch and inter-patch' patterns of natural arid and semiarid vegetation systems (e.g. Greene, 1992; Tongway *et al.*, 2001), and govern their source-sink behaviour (Noy-Meir, 1973).

Planning and management decisions appeared to be important in the establishment of source-sink landscape processes at the experimental site. For example, exclusion of stock from the tree belt has reduced mechanical compaction, encouraged the growth of biological crusts, and helped maintain the litter layer, which protects the surface from consolidation by raindrop impact. Further, the mixture of *Acacia* and *Callistemon* species appeared to provide an appropriate balance in the leaf litter deposition and decomposition rates (i.e. the litter degraded at a rate sufficient to encourage biological activity, but also remained in sufficient quantity to form microterraces in overland flow). The position of the fence at the site, however, and the creation of a bare soil zone, appears at odds with the aim of capturing overland flow. Tree belts established more recently by the farmer have stock exclusion fences further upslope from the tree canopy.

Due to time and resource constraints, this experiment was not replicated spatially. Great care was therefore taken to select a site with similar conditions in each of the two pasture-tree belt sequences and to minimise measurement errors. In addition, two tests for

hydrologic similarity suggested that the spatial variation between the sequences was smaller than the measurement errors. We therefore regard our measurements to be representative of the runoff, infiltration and capture processes observed during the experiment. We also emphasise that, here, we were most interested in the redistribution of water between pasture and trees and that this experiment has addressed these adequately for at our site. While we have shown that a tree belt can capture overland flow from a pasture, we accept that these results are not necessarily transferable to other sites and conditions.

However, our findings build on and confirm some aspects of related studies (McJannet *et al.*, 2000, 2001; Ticehurst, 2004; Ellis *et al.*, 2005b), and are likely to be relevant to farm hillslopes in other regions. That is, the runoff generation and capture processes we observed are likely to occur wherever agricultural land drains onto a tree belt, and the dominant process of downslope movement of excess water is by Hortonian flow.

The relatively rapid succession (i.e. 30 min apart) of the applied rainfall events is likely to have affected our results by pre-wetting the soil and possibly reducing the potential for runoff capture. However, our results show similar  $\Delta S$  (Table 1) for events 2 and 3, although  $C_D$  and  $\Delta P_T$  were much smaller. We would have expected greater capture of the second and third events if they had not been recently preceded (i.e. within 30 min) by other events. But very dry surface antecedent conditions could also produce high runoff rates on some (non-wetting) soils, at least in the early stages of the event and reduce capture. Despite these uncertainties, applying the events in order of increasing magnitude would have somewhat reduced the variation in results, relative to those measured with

different antecedent soil water. That is, the larger the event, the larger the effect on subsequent events, and therefore the smaller the relative effect of antecedent conditions.

Determining responses to a range of soil water antecedent conditions would require further experimental work. Moreover, defining what are the most likely, or most interesting, antecedent conditions for each event is a significant exercise, dependent on soil type, climatic region and design question and outside the brief of this study. It is safe to assume, however, that the proportion of runoff events that can be captured will depend on local soil and rainfall conditions and antecedent soil water content. Of equal, if not, greater importance is the ratio of runoff generation area (hillslope) to runoff capture (tree belt) areas. Field observations during our experiment have also shown the importance of tree litter for slowing and dispersing overland flow, and therefore increasing the opportunity for infiltration.

The capture, and subsequent use, of excess water by trees, however, can be good or bad, depending on the local management objective. If the excess water would otherwise cause waterlogging or dryland salinity lower in the landscape, then using it on site would be good (Silberstein *et al.*, 2002). One could also take advantage of the extra water to increase tree production as suggested by Cooper *et al.* (in press) if the trees provide a commercial product. If these are not potential advantages, then the loss of otherwise productive land to trees may need to be justified in other ways.

Where tree belts are intended for the management of Hortonian flow, thought should be given to the magnitude and frequency of runoff and the likely magnitude and subsequent use of captured water. In this study we simulated 3 rainfall events with local return

periods of 2, 10 and 50 years, applied in relatively rapid succession. The capture of these or other 'design storms' or 'storm sequences' may be critical design parameters for some environments, for example, in landscapes with highly episodic rainfall distributions and runoff events. However, the long-term average effect on water yield may be more important in other areas (Ellis *et al.*, 2005b).



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Table 1 Details of the three simulated rainfall events and resulting water budgets for pasture and for trees.  $\Delta S$  is infiltration expressed in mm,  $C_D$  is captured overland flow and  $\Delta P_T$  is the increase in water supply (due to  $C_D$ ) to the tree belt in addition to incident rainfall. Numbers in parentheses are maximum absolute measurement errors which translate to the ranges in calculated  $C_D$  and  $\Delta P_T$ .

Event	Rainfall duration (min)	Storm return period (yr)	Rainfall depth (mm)	Run-on (mm)		Runoff (mm)		$\Delta S$ (mm)	$C_D$ %	$\Delta P_T$ %
				Trees	Pasture	Trees	Pasture			
1	13	2	10.4 (0.8)	3.6 (0.4)	1.6 (0.2)	0 -	8.8 (1.0)	14.0 (1.0)	100	31-39
2	30	10	24.4 (0.6)	16.2 (2.2)	7.0 (0.9)	2.6 (0.2)	17.4 (1.5)	31.8 (1.7)	32-68	22-45
3	30	50	37.6 (3.6)	38.5 (5.4)	16.6 (2.3)	14.3 (1.3)	21.0 (5.9)	28.6 (7.3)	0-28	0-29

Table 2 Average steady state conditions during rainfall events 2 and 3: infiltration rates  $I_{ss}$  for pasture, trees and a whole sequence of pasture + trees; flow depth  $\bar{D}_c$ , average flow velocity  $\bar{v}$  at rainfall cessation and hydraulic roughness  $n$  for pasture and trees. Numbers in parentheses are absolute measurement errors which translate to the ranges in calculated  $n$ .

Event	Rainfall intensity (mm hr <sup>-1</sup> )	$I_{ss}$ (mm hr <sup>-1</sup> )			$\bar{D}_c$ (mm)		$\bar{v}$ (m s <sup>-1</sup> )		Hydraulic roughness $n$	
		Pasture	Trees	Pasture+trees	Pasture	Trees	Pasture	Trees	Pasture	Trees
2	48.7	31.2	45.3	-	2.3	7.2	0.06	0.02	0.01-0.05	0.12-0.28
	(1.2)	(4.0)	(1.6)	-	(0.3)	(0.5)	(0.01)	(0.00)		
3	75.3	36.5	50.4	41.9	7.5	11.3	0.04	0.03	0.03-0.17	0.08-0.24
	(7.2)	(13.4)	(10.8)	(11.2)	(2.4)	(2.7)	(0.01)	(0.01)		

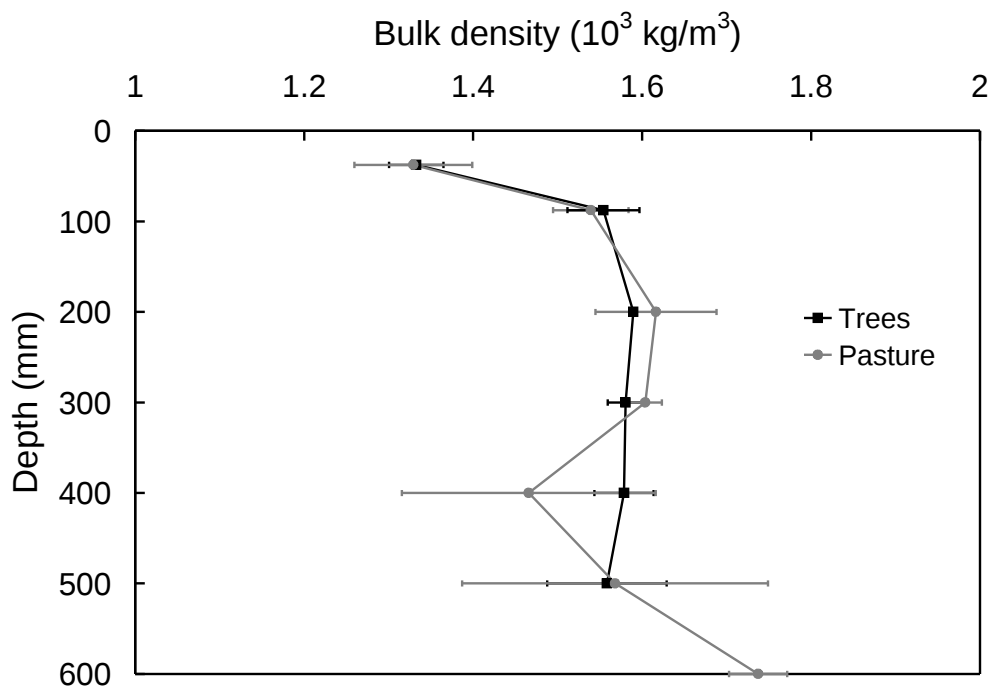


Figure 1 Soil dry bulk density profiles from single pits in pasture and tree plots in the southern sequence. Each data point represents the average of three samples and bars represent one standard deviation each side of the mean.



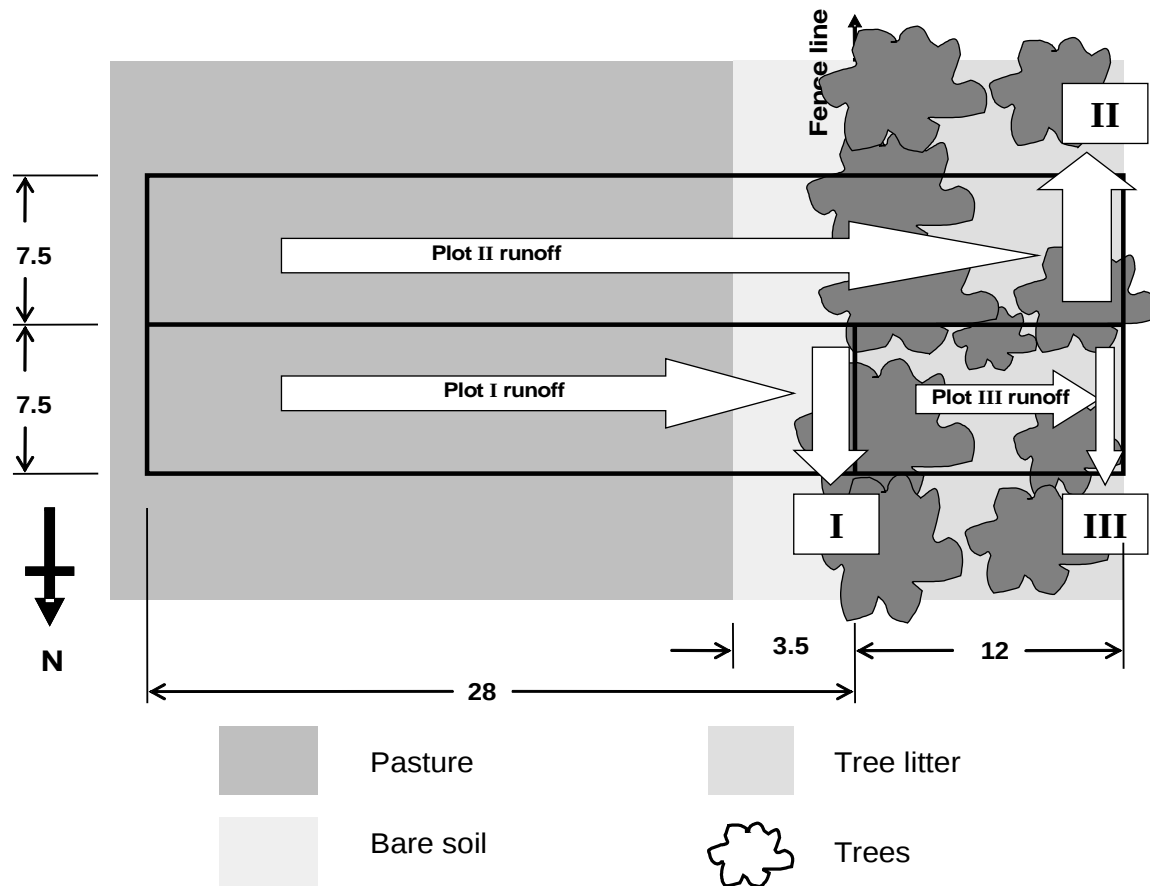


Figure 2 A schematic diagram of the tree belt and plot layout showing dimensions (m). Runoff sampling points for pasture, pasture + trees and trees are shown as I, II and III, respectively.



Figure 3 A view towards the South, over the experimental site, showing Plot I (foreground) and Plot II (middle distance) during the first simulated rainfall event (48 mm/h). Water is beginning to pond on the pasture (left) and bare soil area (right) is generating overland flow, which is draining onto the tree belt (far right). A small backwater can be seen extending about 1 m uphill from the fence on the far plot (plot II).

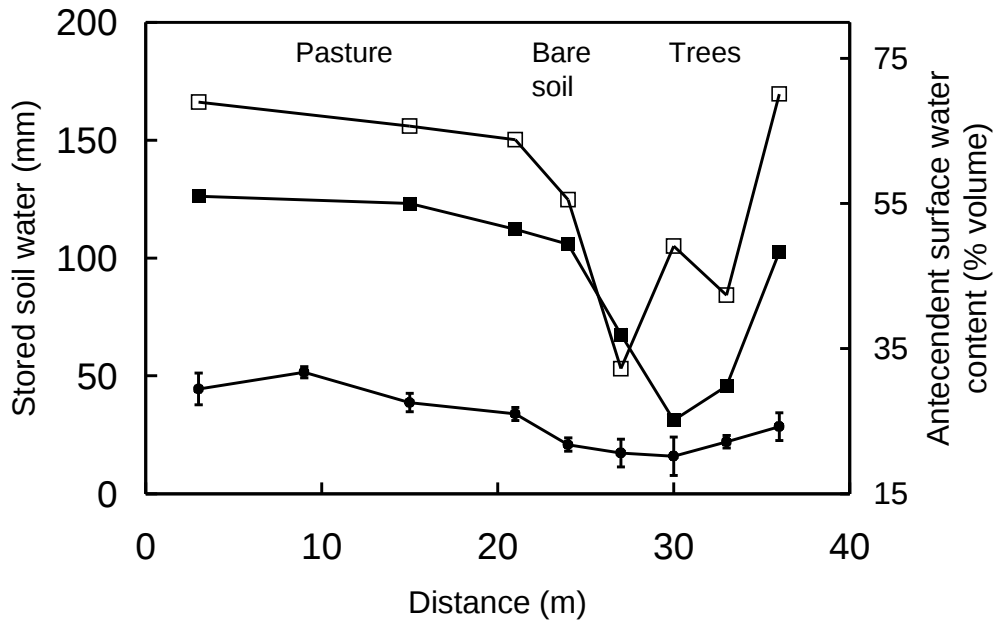


Figure 4 Surface water content 0 to 75 mm deep (●) and stored soil water  $S$  to a depth of 600 mm 'before' (■) and 'after' (□) the experiment. The 'before' transect of  $S$  was taken outside the experimental plot to avoid disturbance of the plot surface and caused the small anomaly at the 28 m position. Error bars on the antecedent soil water represent one standard deviation each side of the mean.

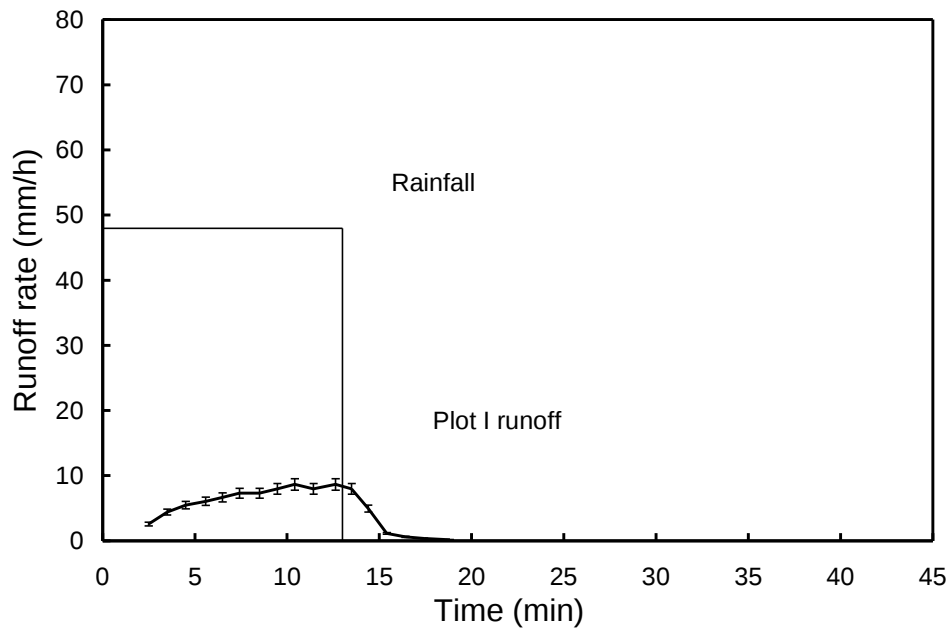


Figure 5 Temporal pattern of rainfall and runoff for the first event for Plot I with nominal rainfall intensity of 48 mm/h. No runoff was generated from plots II and III by this first event. Error bars represent the largest likely measurement error.

Figure 6 Microterraces of organic litter formed within  
overland flow (left) and concentrated over



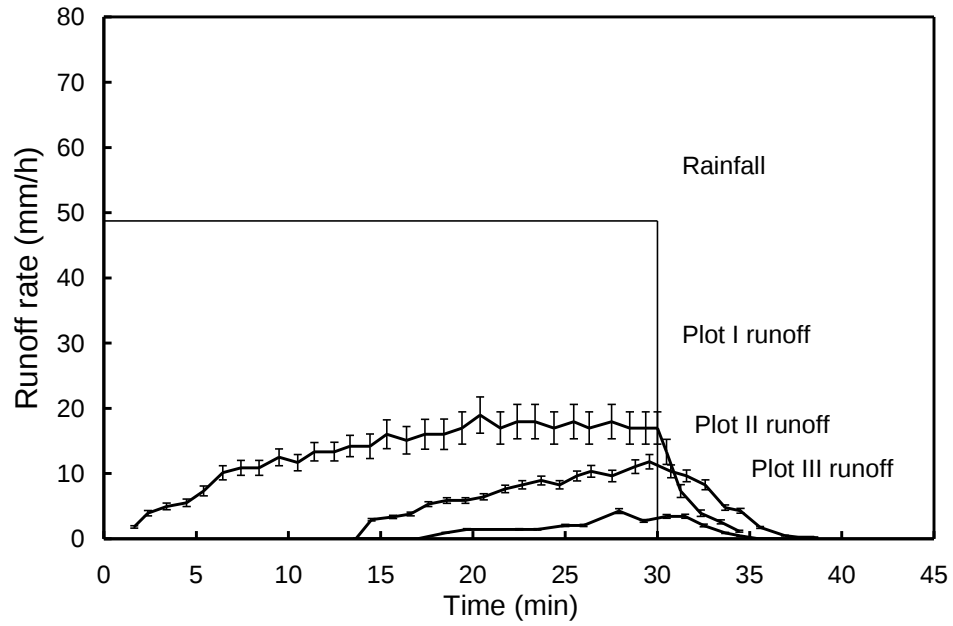


Figure 7 Temporal pattern of rainfall and runoff for the second event with nominal rainfall intensity of 49 mm/h. Error bars represent the largest likely measurement error.

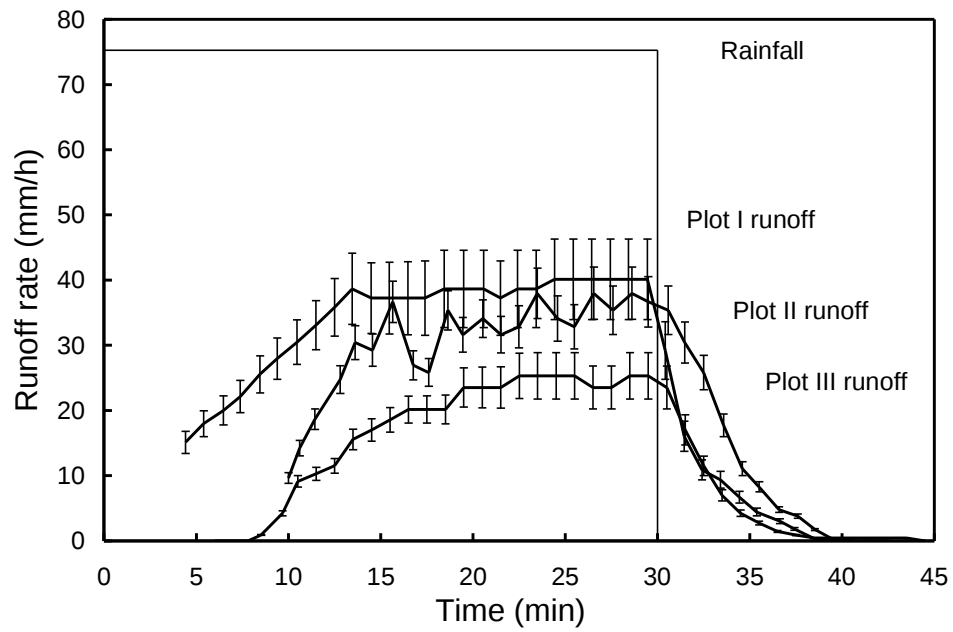


Figure 8 Temporal pattern of rainfall and runoff for the third event with nominal rainfall intensity of 75 mm/h. Error bars represent the largest likely measurement error.