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From water harvesting to crop harvesting: opportunities for efficient use of runoff water by crops *Harrie Lövenstein*

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From water harvesting to crop harvesting: opportunities for efficient use of runoff water by crops

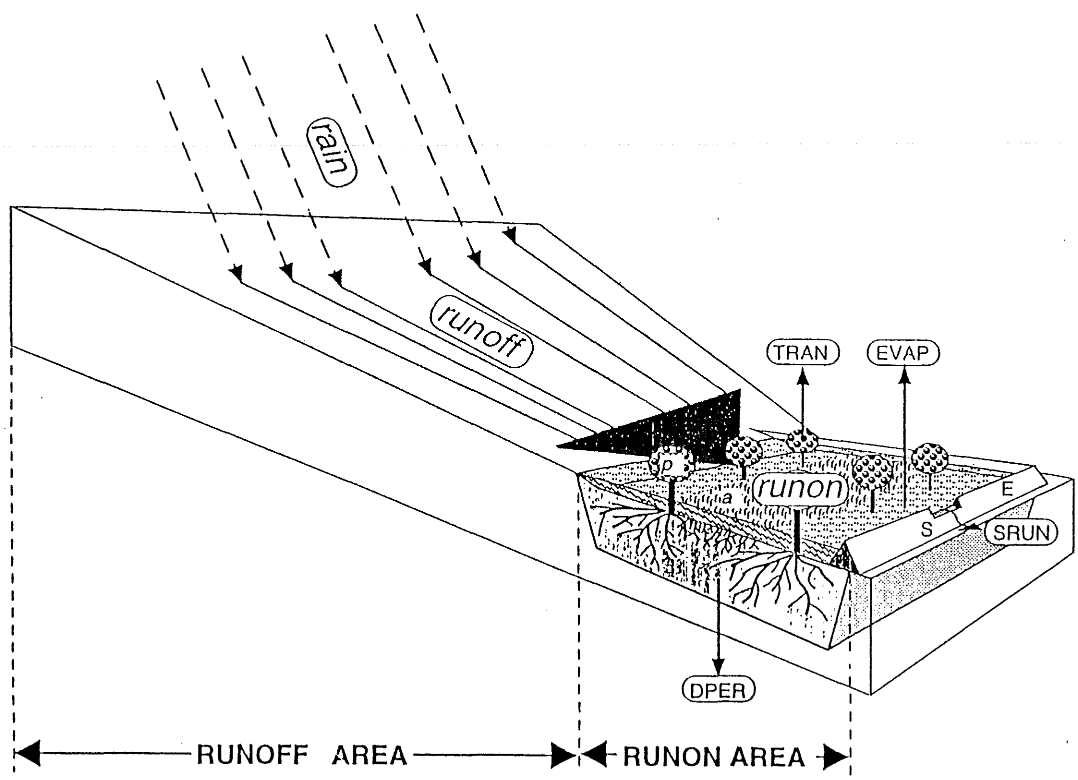
Plant production in arid and semi-arid regions is critically limited by soil moisture availability as a result of low and erratic rainfall, and by nutrient availability (Penning de Vries and Djitèye, 1982). Plant available moisture is further restricted if infiltration rates are reduced by formation of soil crusts and by soil surface evaporation losses, that may account for 60% of the annual rainfall in Sahelian regions at the 450 mm isohyet (Breman, 1992). If rainfall intensity exceeds infiltration rates of the soil, water is generally lost as surface runoff, which additionally may cause soil erosion and the associated loss of nutrients.

Natural vegetation, comprising among others trees and shrubs, counteract soil crusting by absorbing part of the kinetic energy of falling rain drops, thus reducing erosion. The vegetation is, however, subject to deforestation and overgrazing by an increasing human and livestock population, in search for firewood and fodder. More than a billion people, of which a majority lives in these regions, presently experience firewood shortages and this number is likely to almost triple by the end of the century (Agric. Univ. Wageningen 1983). Consequently, the soil looses its natural protection against rain drop impact and erosion, causing soil degradation and dwindling plant production to extend to larger areas. This trend will further threaten food production.

To avert this vicious circle rain water harvesting techniques have been proposed to increase water supply for crop production (Zohar *et al.*, 1988) referred to as runoff farming. These techniques involve the controlled concentration of rainfall as surface runoff from a large watershed or catchment, also denoted as runoff area, into a smaller lower-lying runoff receiving or runon area (Figure 1), also referred to as cultivated area (Boers and Ben Asher, 1982). The latter often consists of agricultural fields or plots trapping large quantities of water, embanked to facilitate their infiltration. As a result, plant available moisture increases, allowing agricultural production in areas that normally do not receive sufficient rainfall. Production of adequate and renewable supplies of food, fodder and firewood under runoff farming conditions, thus reduces the claim on natural vegetation and concomitantly mitigates soil degradation. This holds especially during dry years, when the additional runoff water contributes to a more resilient plant production (Carter and Miller, 1991).

Harrie Lövenstein, Department of Theoretical Production Ecology
Wageningen Agricultural University, Wageningen, The Netherlands

FIGURE 1
Principles of runoff farming. Rain generates surface runoff in a large inclined 'runoff area' which accumulates in a smaller, lower lying and levelled 'runon area'. The runoff water is trapped by a retaining embankment (E) allowing the water to infiltrate into the soil profile. The stored water is subject to losses by evaporation (EVAP) and deep percolation (DPER) which may reduce water availability for crop use in the process of transpiration (TRAN) by annual (a) and perennial (p) crops. The built-in spillway (S) controls losses by surplus runoff (SRUN). The runoff to runon area ratio (RRAR) and spillway height determine the water head in the runon area.



Hydrological aspects of runoff farming are well documented (e.g. Boers and Ben Asher, 1982; Hudson, 1987), but agricultural aspects have received little attention (Reij *et al.*, 1988). The typical growing conditions created by large amounts of runoff water collected a few times per year on one hand, followed by prolonged drought periods on the other, affect plant growth. Often, however, crops are not able to absorb all the runoff water generated. Timing of runoff events may not coincide with the cropping period, whereas their frequency and size may not match crop water requirements. Consequently, part of the water is subject to evaporation losses (EVAP) and deep percolation losses (DPER) and, due to excessive rains, especially when embankments become eroded, to surplus runoff losses (SRUN). As a result, less water is left for transpiration and corresponding biomass production during the drought period.

Runoff losses can be reduced and water shortages prevented when water supply, governed by type of runoff system, and water demand, as determined by crop selection and crop management, are more balanced. This paper will evaluate opportunities for matching runoff system design, crop selection and crop management with the objective to minimize EVAP, DPER and SRUN and to control transpiration, thus allowing plants to produce biomass throughout the dry season.

First, the magnitude of EVAP, DPER and SRUN losses will be discussed for different runoff systems in the absence of crops. Next, crop characteristics are specified that, depending on the runoff system, may increase the effective use of water by the crop through transpiration and its associated biomass production, at the expense of EVAP, DPER and SRUN. Finally, crop management techniques are presented that fine-tune water uptake by crops under fluctuating conditions, common in runoff farming, to optimize water use efficiency.

RUNOFF SYSTEM

Key factors determining the magnitude of runoff generation in the catchment area comprise rainfall characteristics (among others rain intensity and duration), soil properties (a.o. texture, surface roughness due to vegetation and stoniness) and topography (Ben Asher *et al.*, 1985; Yair, 1983). This is expressed in the runoff efficiency, i.e. the ratio of runoff volume to precipitation volume averaged over a year to discount variability due to storm size (Fink *et al.*, 1979). Runoff efficiency increases with rain intensity, fineness of soil texture, and steepness of slope, but decreases with catchment size (Evenari *et al.*, 1982). In larger catchments surface runoff has to cover longer distances, implying a longer retention time during which it is subject to infiltration losses. This longer time span also explains the longer response time for larger catchment areas to generate runoff if at all, during low-intensity or short duration rains.

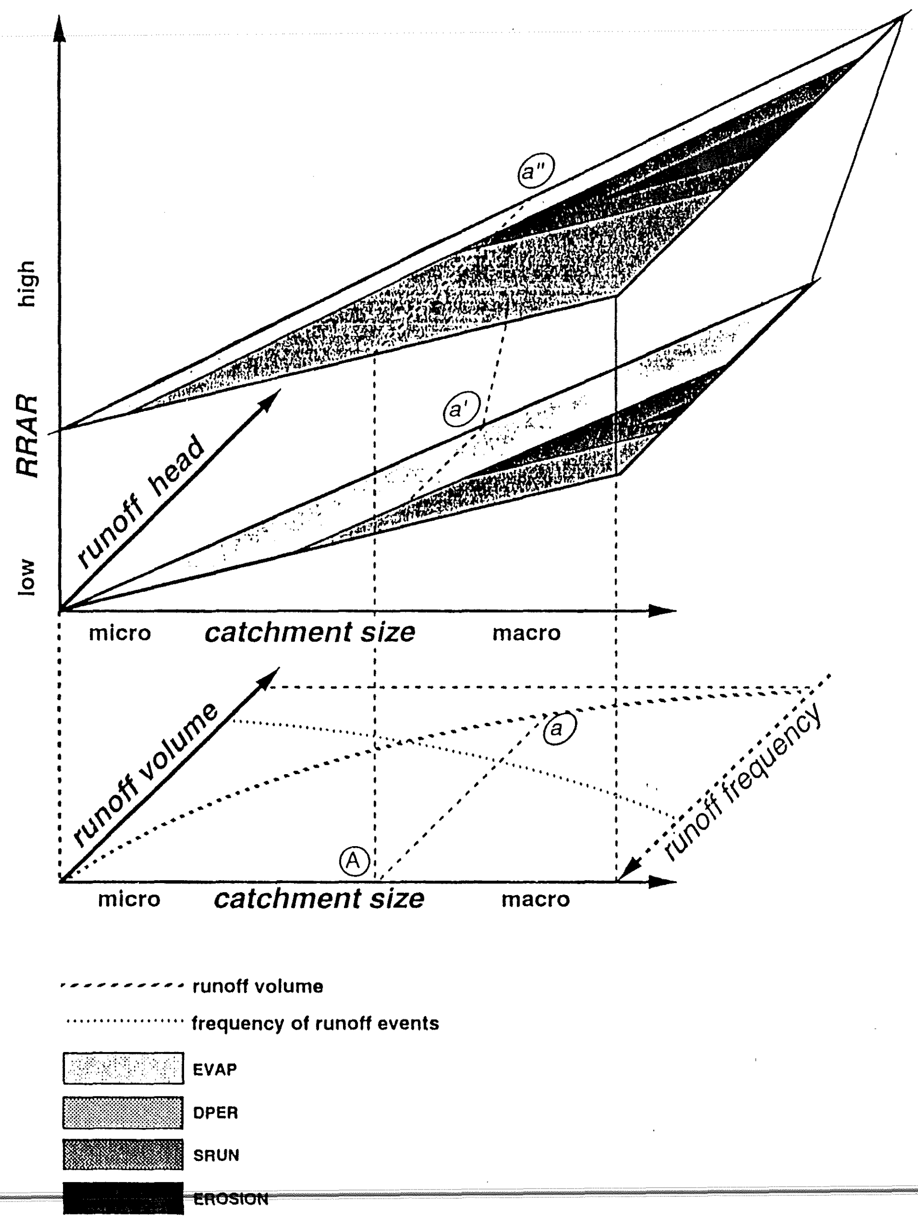
Assuming other runoff determining factors characterizing a region constant, overall runoff production increases with size of the catchment area, though at a decreasing rate as runoff efficiency declines (Figure 2). The head of water ponded in the runon area, and thus the infiltration depth, is co-determined by the runoff to runon area ratio (RRAR): higher RRAR's generally lead to deeper infiltration. The desired RRAR depends on the water storage capacity of the soil profile in the runon area, which follows, in principle, from soil depth and soil texture (Boers and Ben Asher, 1982) and, ideally, crop water requirement. Large catchment areas are often associated with higher RRAR's, because the inherently lower runoff effiencies require less than proportionally expanded runon areas to maintain an adequate depth of infiltration. Hence, runoff systems can be classified according to the size of their catchment area, here conveniently distinguishing between micro-catchment ($\leq$ 5 ha) and macro-catchment systems ($>$ 5 ha), and their associated RRAR's.

Micro-catchments

Micro-catchments respond rapidly to rain, including light showers, by generating small amounts of runoff (Shanan and Tadmor, 1979; Boers *et al.*, 1986), that generally do not create erosion problems. As a result, the soil profile in the runon area may be frequently wetted during the rainy season by limited amounts of water. At RRAR $<$ 10, typical for micro-catchment systems, like shallow pitting (runon area $<$ 0.5 m^2) or 'zay' in Burkina Faso (Reij *et al.*, 1988) and (tied) contour strips as series of micro-catchments in Kenya

FIGURE 2

Sources of potential water losses from the runon area and their magnitude (in arbitrary units) as determined by catchment size and RRAR in the absence of crops. The runoff volume in the runon area increases and the frequency of runoff events decreases with increasing catchment size (indicated by the curves in the bottom plane). When catchment size (A) and corresponding runoff volume (a) are constant, waterhead in the runon area increases with RRAR (from a' to a") as the size of the runon area declines. As a result, contribution of EVAP decreases and those of DPER and SRUN increase with RRAR, gradually leading to erosion in extreme situations. The upper and bottom 'triangles' represent the boundaries of the space of choices in which RRAR, associated with soil depth and texture, and catchment size may vary. Note that RRAR tends to increase with catchment size. (For explanation of abbrevations, see Figure 1.)



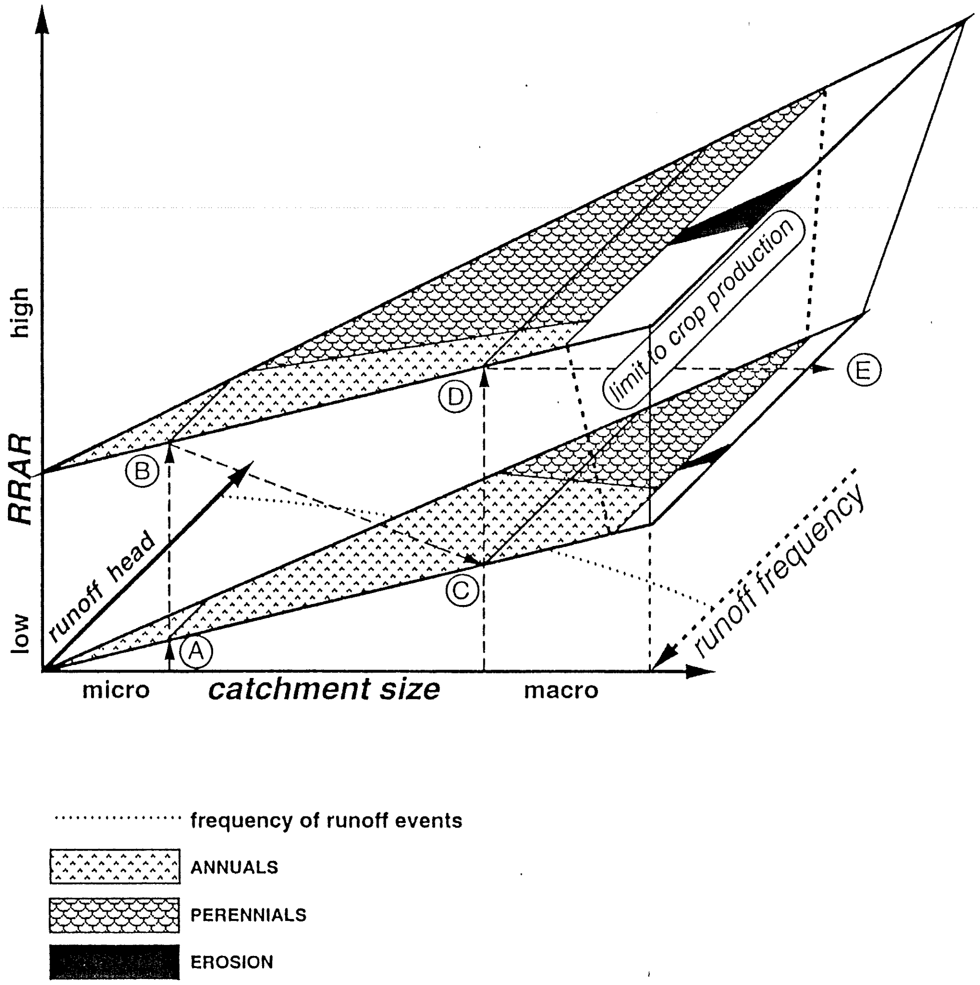
(Hudson, 1987), soil profiles are wetted rather superficially, especially in fine textured soils. This implies that a large proportion of the trapped runoff may be lost as EVAP (Figure 2), particularly during light summer rains. Increased RRAR's, as found for hill-side ditches and semi-circular hoops in Kenya (Reij *et al.*, 1988), thus reduce EVAP but may induce DPER, particularly in coarse textured soils, as well as SRUN (Figure 2), following heavy storms (Boers and Ben Asher, 1982). Although this seems to indicate that systems with lower RRAR's are preferable in coarse textured soils, inherently poor runoff yields due to low runoff efficiencies (i.e. high infiltration losses during prevailing low-intensity rains), may necessitate maintaining relatively high RRAR's nonetheless. Similarly, adjusting RRAR to lower values should be considered on fine textured soils in regions dominated by high intensity rains, as runoff efficiency is higher in such systems. Reducing RRAR's, particularly in runoff systems on the latter soil types, is also required to reduce the retention time of water standing in the runon area and thus the risk of waterlogging.

As distance between runon areas increases with RRAR in runoff systems of interlinked micro-catchments, individual plants become more exposed to the high radiation load and drying power of the air, typical to (semi-)arid regions (Eastham *et al.*, 1988; Berliner, personal communication). Consequently, higher transpiration rates per unit runon area are likely, without additional dry matter production, which may nullify the effect of improved water supply due to relatively high runoff efficiencies of micro-catchments. In addition to the water directly withdrawn from the small runon area (i.e. EVAP, DPER and transpiration), a substantial amount of water appears to be lost by evaporation from the soil surrounding this area, as a result of lateral subsurface flow from the runoff water stored in the soil (Berliner, personal communication). This is sometimes witnessed by salt precipitated at the soil surface (Orev, 1986). To some extent, salt accumulation with its adverse effect on crop growth, may also occur within the runon area, due to inadequate leaching by a limited runoff head, resulting from low RRAR's or low runoff efficiencies (e.g. light showers). Rather than promoting leaching through increased DPER by contraction of runon areas, salt accumulation may be prevented by application of (stone) mulch, concurrently saving additional water for plant use.

Macro-catchments

As a consequence of the lower runoff efficiencies inherent to larger catchment areas, macro-catchments produce runoff less frequently than micro-catchments, though at larger volumes with additional erosion hazard. The occasional production of large amounts of runoff requires macro-catchment systems characterized by high RRAR and preferably fine textured soils, to assure adequate runoff storage in the runon area, especially during drier years. Examples can be found in Kenya and Israel in the form of trapezoidal or contour bunds of 0.25-1 ha in size with RRAR's of 15-50, and spate or diversion systems with runon areas of 1-10 ha and substantially higher RRAR's (Evenari *et al.*, 1982; Finkel, 1985). EVAP is small relative to the amount of water stored in the soil, though DPER may be considerable (figure 2), particularly in coarse textured soils. In practice, both types of losses may be of similar importance due to inadequate levelling of sizable runon areas: parts receiving insufficient or too much runoff are mainly subject to EVAP or DPER, respectively. Hence, smaller runon areas are preferable, to facilitate control of the water distribution. At high-intensity rains, however, runoff volumes, amplified by the large catchment area, will readily exceed storage capacity of the runon area. The consequently high discharge rates may lead to exceptionally high SRUN (Figure 2), accompanied by erosive forces, detrimental to the (embanked) runon

FIGURE 3
Crop selection, determined by the runoff system, characterized by catchment size and runoff to runon area ratio (RRAR). Suitability of annuals decreases and that of perennials increases with increasing catchment size and RRAR, as indicated by the transects at A, B, C and D (further explained in the text). Crop production beyond the right face (E) of the object, representing the space of choices, is not recommended, due to increased erosive forces damaging the runon area and its embankements which may lead to reduced runoff retention.



area and its crops. Hence, spillways (Figure 1) should be constructed to safely control the outflow of excess runoff while maintaining a water head between 0.2 - 0.5 m (among others Critchley, 1987; Pacey and Cullis, 1986; Carter and Miller, 1991), at which an adequate amount of water is trapped for biomass production, without creating waterlogging problems common in fine textured soils. In terrace systems with series of bunded fields, excess runoff cascades along spillways from upper fields into lower ones, resulting in an even water distribution in the fields comprising a large runon area. In the latter situation, RRAR may have decreased to values that preclude bottom fields from receiving runoff water in drier years. This may be remedied by harvesting runoff from adjacent hills through conduit channels (Evenari *et al.*, 1982), thus improving runoff efficiency by a reduced length of slope.

The large amount of water concentrated in macro-catchment systems supports high plant densities. Provided runon areas being sizable enough, like (diversion systems of) terraced fields, the associated improved micro-climate, characterized by reduced drying power of the air may curtail excess transpiration, as suggested for crops in widely spaced micro-catchments. Moreover, EVAP directly around the runon area, fed by subsurface lateral flow, is negligible compared to the amount of water ponded. Although leaching, as a result of recurring high runoff volumes, reduces salinization hazard in the runon area, essential nutrients may be lost in the process.

CROP SELECTION

In general, crops considered for growth under runoff conditions should be screened for high and resilient food, fodder and firewood production and, for shrubs and trees, reliable regrowth after grazing or coppicing. Not less important, they should tolerate periods of prolonged droughts, which may include salinity stress, as well as brief, intermittent periods of waterlogging during runoff events. In addition to crops native to arid lands, also those common to higher rainfall areas, among which grapes (Evenari *et al.*, 1982) and *Leuceana leucocephala* (Lövenstein *et al.*, 1989), may be considered following the increased water availability by runoff collection. Leguminous species, like the latter, are of particular interest as they may improve the nitrogen status of the soil.

The different runoff systems impose various growing conditions on the crop, as characterized by the amount of runoff water supplied, the frequency of runoff events (both associated with catchment size) and the depth of infiltration (mainly depending on RRAR). Hence, crop selection and associated water use are strongly linked to the type of runoff system applied.

Selected crops should balance their water use through transpiration against runoff supply, thus limiting the time soil moisture is subject to EVAP and DPER. A distinction is made between overall water uptake during the growing season of the crop and daily water uptake, as reflected in the transpiration rate, because the former obscures moments of abundant water availability directly after a runoff event, and of water deficiency later in the season.

Overall crop water requirement

Overall water requirement of annual crops is generally less than that of perennial crops like shrubs or trees. Moreover, they require more frequent wetting of a relatively shallow rooting zone than the generally deeper rooting shrubs or trees which, therefore, may perform satisfactorily at rather infrequent events of water replenishment. Water requirement and rooting depth of annual and perennial crops may thus be well linked to the specific conditions created by micro- and macro-catchments and their associated RRAR's.

Micro-catchments with low RRAR preferably on fine textured soils are eminently suitable for annual crops (figure 3, A), provided that other crop requirements, such as temperature regime and day length, are met in the rainy season at the onset of runoff events. Despite the relatively frequent and shallow wetting of the soil with negligible DPER, EVAP remains small due to water withdrawal by the crop and shading by its canopy. This implies that trapped runoff mainly contributes to transpiration and corresponding biomass production (Table 1).

TABLE 1

Effect of runoff system/crop slection combinations on losses by evaporation, deep percolation and surplus runoff (EVAP, DPER and SRUN, respectively) and on the degree of stress caused by waterlogging and water shortage for transpiration (WLOG and TRAN-S, respectively). Note that results presented under DPER, SRUN and WLOG are identical, and approximately reverse to EVAP. Moderate to severe SRUN is accompanied by increasing erosion hazard. RRAR represents runoff to runon area.

Symbols in order of increasing severity: – none -> +/– slight -> + moderate -> ++ severe

An increasing number of O and ● correspond with higher amounts of runoff in the runon area or frequency of runoff events, respectively.

catchment size	RRAR	runoff amount	frequency events	crop	EVAP	DPER	SRUN	WLOG	TRAN-S
micro	*low*	o	●●	annual	+/–	–	–	–	+/–
				perennial	++	–	–	–	+
	high	oo	●●	annual	–	+/–	+/–	+/–	–
				perennial	+	–	–	–	+/–
macro	*low*	ooo	●	annual	+/–	+	+	+	+/–
				perennial	+	+/–	+/–	+/–	+/–
	high	oooo	●	annual	–	++	++	++	+/–
				perennial	+/–	+	+	+	–

At higher RRAR's micro-catchment systems on fine textured soils become less suitable to annuals (Figure 3, B), as these crops may experience waterlogging (Table 1), particularly during critical periods like emergence. Following infiltration of the runoff water submerging the crop, soil crusts are formed that may impose mechanical resistance to emerging seedlings, whereas existing leaves are mud covered, so that photosynthesis is impaired. Since such conditions inevitably lead to total crop failure, reseeding would be required. Waterlogging at later and less critical development stages is less detrimental to most annual crops, provided its duration is limited to 1 or 2 days. This may be achieved by adjusting RRAR to soil texture (i.e. increasing runon area) or reducing spillway heights. However, as these measures may conflict with the need of storing adequate amounts of runoff water, annual crops with lower water requirements should be cultivated instead.

As water supply and depth of infiltration increase with RRAR, also consecutively perennial grasses, shrubs and trees may be grown in the runon area (Figure 3, B). Under these conditions anticipated DPER is restrained, although EVAP may be higher under single shrubs or trees as the soil surface is less effectively protected against radiation and drying power of the air (Table 1). When shrubs or trees shed their leaves under drought stress, resulting from inadequate amounts of water stored in the soil, EVAP may be high after a subsequent runoff event. Considering the low runoff volumes involved, increased EVAP may induce salinization, which limits crop choice. Shrubs and trees within relatively small runon areas are generally less affected by waterlogging, especially when limited to less than a week. At longer retention periods, common in hill-side ditches or similar structures of 0.5 - 1.0 m depth on fine textured soils, trees and shrubs are preferably planted next to the runon area rather than inside (Orev, 1986).

As catchment size increases, infrequent water supply may exclude cultivation of annual crops characterized by relatively shallow root systems (Figure 3, C), that may lead to relatively high DPER, unless deep rooting species or perennials are grown (Table 1). An additional advantage of perennials here is, that the soil is better protected against erosive forces. However, EVAP may be relatively high, as the amount of plant available water limits the number of shrubs or trees providing ground cover (Table 1). Drought tolerant species with low water demands are most promising in this situation.

When plant available water in macro-catchments increases with RRAR (Figure 3, D) green shrubs and trees can be grown for a longer period to protect the soil surface against high EVAP (Table 1). In years characterized by frequent runoff events, DPER may increase, although deep rooting species tend to intercept this water during the dry season. In some specific situations deep-percolated water may flow as subsurface runoff to adjacent fields and be utilized by crops after all (e.g. in series of terraced fields). During extreme runoff events, waterlogging may even affect tree growth in macro-catchment systems. Reducing spillway height, thus increasing SRUN, at the expense of water storage, may lead to lower biomass production. Hence, trees/shrubs should be selected with higher tolerance to waterlogging, like *Eucalyptus camaldulensis* or to water shortage, like *Acacia nilotica* or *Casuarina glauca*.

Introducing more water in the runon area by increasing catchment size or RRAR further (Figure 3, E) is not favorable. While crops are unable to absorb the additionally generated runoff water and waterlogging problems aggravate, the occasionally high SRUN with associated erosive forces may cause severe damage to the runon area and its crops.

Transpiration rate

Annual or perennial crops, maintaining high transpiration rates, also during periods of moderate drought stress, are preferred as they exploit the runoff water effectively. Such crops, like *Phalaris minor*, an annual grass (Lof, 1976), and *Eucalyptus occidentalis*, a firewood producing tree (Lövenstein *et al.*, 1989), are referred to as water 'spenders' (Lof, 1976). While stomata are open, 'spenders' show high assimilation rates at high radiation levels, typical in arid regions, and consequently, high growth rates. Hence, 'spenders' are generally characterized by a high water use efficiency in terms of biomass produced per unit runoff stored in the soil. When 'spenders' exhaust available soil moisture before completing their development cycle, however, annuals may not be able to produce seeds or other storage organs, whereas perennials may shed their leaves or finally die. In such situations species are preferred, that show stomatal closure at moderate drought stress, thus saving water for crop growth over a longer period of time. Such crops, like *Hordeum murinum*, an annual grass (Lof, 1976), and *Acacia salicina*, a fodder and firewood producing tree (Lövenstein *et al.*, 1989) are, therefore, referred to as water 'savers' (Lof, 1976). The curbed transpiration rates of 'savers' and the consequently higher EVAP and DPER, may lead to lower water use efficiencies, especially when growth rates are limited too.

Water availability in runoff systems permitting, 'spenders' are thus preferred to 'savers'. Annual 'spenders' with a very short life cycle (< 2 months), like tepary bean (*Phaseolus acutifolius*), may perform well in micro-catchment systems with high RRAR (Lövenstein *et al.*, 1989). At lower water availability, annual or perennial savers should be considered, especially at unavoidably low RRAR's, required in shallow or fine textured soils. In macro-catchments with relatively high RRAR's, large runoff volumes may compensate for the infrequent runoff supply, allowing annual and perennial 'spenders' to be grown.

However, as runoff volumes or frequency of runoff events decline in lower rainfall areas, 'savers' become a better bet to produce at least some biomass.

Heterogeneous water distribution, common in series of terraced fields and inherent to inadequately levelled fields, requires the concurrent use of a variety of crops. Areas receiving reliable amounts of runoff on an annual basis (i.e. top terrace fields or lower spots within a field), should be cultivated under perennials enabling the immediate use of runoff when generated. As cultivation of perennials becomes too risky in the remaining, drier parts, especially in relatively dry years, facultative production of annual crops should be considered: seeding starts once adequate amounts of runoff water have been collected, thus reducing the risk of crop failure under highly erratic runoff conditions.

CROP MANAGEMENT

Besides by crop selection, total water use and rate of water uptake are also affected by crop management, such as crop configuration (i.e. plant density and crop mix), cropping calendar (i.e. planting dates, coppice rotations) and nutrient application. Hence, crop management provides additional means to further reduce EVAP, DPER and SRUN in favour of transpiration.

In general, EVAP decreases with increasing plant density due to increasing soil cover and concurrently, by intensifying water uptake from the profile. The latter may lead to increased rooting depth, thus reducing DPER as well. However, because of their permanent presence, crowding of trees or shrubs may result in prohibitively high water consumption during drier years with adverse or even fatal consequences for 'spenders'. This also applies to inclined fields, as in trapezoidal bunds (Finkel, 1985), with a corresponding gradient in water availability, which requires plant density to be adjusted accordingly. On the other hand, during wetter years or on wetter spots, lower tree densities increase soil surface wetness duration, attracting water consuming weeds. Weeding or mulching is then recommended, which may be achieved in one operation, as a soil mulch is formed in loamy soils after harrowing or rotorvating (Evenari *et al.*, 1982).

Alternatively, a similar effect may be achieved by introducing an annual intercrop, as proposed in runoff agroforestry (Lövenstein *et al.*, 1991), that is likely to consume water from the upper layers, part of which would otherwise evaporate directly from the soil surface after a runoff event. Deeply percolating water can be exploited by trees or shrubs with deep root systems, without competing with the annual crop. In this way, limited competition between *E. grandis* and pasture has been explained by their different rooting patterns, leading to water withdrawal from different soil layers (Eastham and Rose, 1990). Competition for light may be reduced as trees like *Acacia albida* (Felker, 1978), or *Leuceana leucocephala* (Lövenstein *et al.*, 1989) shed their leaves in the rainy or cold season, respectively, during which an annual crop may benefit from the rains, which may not always generate runoff.

In addition to the spatial and temporal complementarity in water use, also direct synergistic effects can be identified, that contribute to higher biomass production. The presence of an adequate number of transpiring trees in macro-catchment systems may lead to higher relative humidity, with a moderating effect on transpiration rate of annuals (Eastham and Rose, 1988) without necessarily increasing EVAP and DPER. In turn annuals, withdrawing water mainly from the upper soil layers, may force trees to extend their rooting depth, while exploiting these deeper layers with relative ease, provided sufficient water is available (Lövenstein *et al.*, 1991). Moreover, a high water content in these layers appears to compensate for the additional resistance to water uptake due to a longer transport path, so that trees do not explore surface layers intensively, allowing annuals to utilize the residual water (Lövenstein *et al.*, 1991). Other reports suggest that tree roots may loose water near the soil surface, favoring the annual crop (Baker and van Bavel, 1988; Hector *et al.*, 1993).

Runoff agroforestry systems, furthermore, are expected to be fairly resilient under fluctuating conditions by mitigating crop failures. During drier years, annual crops can optionally be omitted to avoid or reduce drought stress development in the tree crop. Because timing and frequency of rainfall are unpredictable, perennial 'savers' combined with annual 'spenders' may be a promising system for the simultaneous and resilient production of food, fodder and firewood.

As water consumption increases with tree size, regular thinning or felling is required to avert drought stress development and the associated decline in growth rate (Lövenstein and Berliner, 1994). Timing of these operations should, however, be such, that coppice shoots can generate during favorable periods. Only on these occasions firewood and fodder should be harvested. As long as coppice shoots are small, EVAP may be restricted by annual intercropping. Growing conditions for the intercrop are markedly improved as competition for light is alleviated after tree harvesting.

Nutrient deficiency limits crop growth, including the formation of a transpiring leaf area. Hence, stored runoff water may not be fully used by a crop under nitrogen limitation (Penning de Vries and Djitèye, 1982), while water use efficiency is negatively affected (de Wit, 1992). The erratic runoff events may seriously reduce recoveries of applied fertilizers. Prior to a runoff event, fertilizer applications may lead to deep percolation of nutrients beyond the reach of shallow rooting annuals. Fertilizer applications after a runoff event without any subsequent rain or runoff may also turn out unfavorable: shallow rooting of annuals is encouraged, which may lead to aerly drought stress, whereas nutrients may be out of reach of deep root systems of perennial crops. Introduction of leguminous crops could be promoted and soil erosion prevented to improve the nutrient status of the soil and the associated biomass production.

CONCLUSIONS

Designs of runoff systems often focus on harvesting water rather than on harvesting crops. Both, shortage and excess of runoff, in relation to crop requirements are reflected in lower water use efficiencies, as a result of EVAP, DPER, SRUN, drought stress and waterlogging. The harvested runoff volumes and the frequency of runoff events should be tuned to overall water requirements and transpiration rate of crops in time and space and vice versa. The following steps in planning runoff farming systems are suggested to increase water use efficiencies:

First, based on soil and climatic factors, maximum catchment size and associated runoff volumes should be determined at which peak discharge rates generated during runoff events do not exceed acceptable probability levels with respect to erosion. Smaller catchment sizes may be preferred because of their lower labour and maintenance requirements.

Next, based on estimated mean annual runoff production, RRAR is assessed by considering the water storage capacity of the soil (soil depth and texture) and the minimum water requirement and maximum rooting depth of desired crops. The range of crop choice should be adjusted to the anticipated amount and frequency of generated runoff.

Finally, crop management provides additional means to adjust to fluctuations in mean annual runoff yields and timing over the year, by adapting plant density and optional use of intercrops. Especially the combined cultivation of shallow rooting annuals and deep rooting perennials appears to lead to efficient use of stored water, while allowing the simultaneous production of food, fodder and firewood.

As more quantitative relationships are established between the factors discussed in the above steps, expert systems may be developed for increasing crop production and improving its resiliency through increased water use efficiency in runoff farming.

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