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No Runoff, No Soil Loss:
soil and water conservation
in hedgerow barrier systems

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hoogleraar in de cultuurtechniek van de regenafhankelijke landbouw

Stellingen

1. De hoeveelheid grond die van een helling afspoelt wordt over het algemeen berekend als functie van klimaat- en bodemeigenschappen en zelden als functie van afstroming, zoals eigenlijk zou moeten. Er vindt immers geen grondverlies plaats zonder afstroming.

Dit proefschrift

2. Het toepassen van het 'design storm' criterium als standaard voor het ontwerpen van bodem- en waterconserveringsmaatregelen dient te worden vervangen door het toepassen van het 'design event' criterium, omdat de hoeveelheid materiaal die afspoelt afhankelijk is van een samenloop van optredende omgevingsfactoren en niet alleen afhankelijk is van de grootte van de storm.

Dit proefschrift

3. De huidige opvatting in bodemconservering dat de bedekking van de bodem belangrijker is dan een erosiebarrière is niet realistisch voor droge gebieden, waar ten gevolge van een lage plantaardige produktie de kansen voor een voldoende bodembedekking vaak gering zijn.

Dit proefschrift

4. Het planten van anti-erosieheggen blijkt in droge gebieden zeker even succesvol te zijn als in natte gebieden, waar deze techniek oorspronkelijk tot ontwikkeling kwam.

Dit proefschrift

5. Op hoogtelijnen geplante heggen verminderen bovengrondse afstroming, in de eerste plaats doordat de infiltratie onder de heggen een veelvoud is ten opzichte van de oorspronkelijke infiltratie - waardoor een groot deel van de afstroming alsnog in de bodem terecht komt - en pas in de tweede plaats doordat de heggen een obstakel vormen voor afstroming.

Dit proefschrift

6. De mogelijkheden van biologische erosiebestrijding, die goedkoper in aanleg zijn en minder gevaar opleveren bij eventuele overstroming dan cultuurtechnische maatregelen, worden nog te weinig gedetailleerd onderzocht.

A. Young, 1989. Agroforestry for soil conservation. CAB International and ICRAF, Wallingford
N.W. Hudson, 1992. Land Husbandry. Batsford, London

7. De conclusie van Ratan Lal dat het telen van koeiebonen een betere bodemconserveringsmaatregel is dan het telen van maïs wordt niet door zijn gegevens gesteund, aangezien in zijn onderzoek de gewassen consequent in twee verschillende seizoenen werden verbouwd; maïs enkel in het 'major' seizoen en koeieboon in het 'minor' seizoen.

Lal, R., 1989. Agroforestry systems and soil surface management of a tropical alfisol I: soil moisture and crop yields. Agrofor. Syst., 8: 7-29

8. De uitspraak dat een bodem aan het begin van het groeiseizoen uitermate gevoelig is voor erosie - omdat het land dan onbegroeid is - is te simpel. In veel subhumide en semi-aride gebieden is het bodemprofiel droog aan het begin van het groeiseizoen, met vaak tegelijkertijd een zeer hoge infiltratiecapaciteit die afstroming voorkomt en afspoeling verhindert.

9. Bij het analyseren van problemen met betrekking tot bodemerosie is een grondige kennis van de geologie en met name van de geomorfologie wenselijk. Het feit dat meer dan de helft van alle akkers en weilanden ter wereld op een helling ligt, illustreert de omvang van potentiële erosie en onderschrijft het belang van de geomorfologie. Het voornemen in Wageningen om de leerstoel Geologie op te heffen doet vermoeden dat de bedenkers hiervan nimmer buiten Nederland zijn geweest en roept vraagtekens op bij het predikaat 'Internationaal' van de Landbouwwuniversiteit.
10. Het verdient aanbeveling de Latijnse plantennamen *Pinus*, *Picea* en *Abies* te vertalen in respectievelijk pijn, den en spar, in plaats van de huidige namen den, spar en zilverspar. Behalve dat de pijnboom weer zijn rechtmatige plaats in de Nederlandse flora terugkrijgt, zou dit eveneens tot gevolg hebben dat Nederlandse kinderen weer met een gerust hart 'oh, denneboom' kunnen zingen, zonder dat de eerste de beste plantennaam die zij spelenderwijs leren meteen een foutieve is.
11. Dat de alcoholconsumptie in Nederland sinds de vijftiger jaren per hoofd van de bevolking vervijfvoudigd is blijkt niet alleen uit de officiële verkoopcijfers, doch ook duidelijk uit de ontwerpen van menig stratenpatroon in hedendaagse nieuwbouwwijken.
12. Na het indienen van een manuscript bij een van de gerenommeerde wetenschappelijke tijdschriften voelt de schrijver zich vaak als een speelbal in een flipperkast, waar anonieme collega's als waanzinnigen op de knoppen te keer gaan.
13. De geringe afmeting van het kader waarin een handtekening op een betaalpas dient te worden gezet leidt maar al te vaak tot het aanpassen of zelfs totaal verminken van de gangbare handtekening, wat vaak problemen oplevert met legitimatie.
14. A hedge between keeps friendship green.

Paul Kiepe

'No Runoff, No Soil Loss: soil and water conservation in hedgerow barrier systems'.
Wageningen, 11 september 1995

Propositions

1. The amount of soil being lost through water erosion is often estimated as a function of climatic and edaphic properties, but seldom as a function of runoff, as it ought to be. For there is no soil loss without runoff.

This thesis

2. The application of the concept of 'design storm' as a standard for designing soil and water conservation measures should be replaced by the application of the concept of 'design event', because it is a concurrence of circumstances that is decisive for the amount of soil being lost and not just the magnitude of the storm.

This thesis

3. The present trend in soil conservation research that the presence of soil cover is more important for soil conservation than the presence of an erosion barrier is not realistic for dry areas where, due to a low biomass production, the chance to obtain an adequate soil cover is often small.

This thesis

4. Planting hedgerow barriers for soil and water conservation in dry areas appears at least as successful as in humid areas, where this technique was originally developed.

This thesis

5. Contour-planted hedgerow-barriers decrease runoff in the first place because the infiltration beneath the hedgerows is manyfold the original infiltration, which causes part of the runoff to infiltrate, and in the second place because the hedges form a physical obstacle to runoff.

This thesis

6. There is still not enough research into the processes of biological measures to reduce runoff and erosion, which are cheaper to establish and less dangerous in case of overtopping than mechanical measures.

A. Young, 1989. Agroforestry for soil conservation. CAB International and ICRAF, Wallingford
N.W. Hudson, 1992. Land Husbandry. Batsford, London

7. The conclusion drawn by Ratan Lal that growing cowpea is better for soil conservation than growing maize cannot be drawn from his research data, because the crops were grown for six years consequently in two different rainy seasons; maize exclusively in the major season and cowpea in the minor season.

Lal, R., 1989. Agroforestry systems and soil surface management of a tropical alfisol 1: soil moisture and crop yields. Agrofor. Syst., 8: 7-29

8. The statement that soils are prone to erosion at the start of the cropping season because the fields are bare is too simple. In many subhumid and semi-arid areas the soil profile is dry at the start of the cropping season, while it has often simultaneously an initially-high infiltration rate that absorbs incipient runoff and, therefore, inhibits soil loss.

9. A thorough knowledge of geology and in particular geomorphology is most welcome for the analysis of soil erosion processes. More than half of the agricultural land in the world is situated on slopes, which illustrates the scale of potential erosion and emphasises the importance of geomorphology. The intention to abolish the chair of Geology in Wageningen makes one wonder if the advocates have ever been abroad and questions the title 'International' when applied to Wageningen Agricultural University.
10. It is recommended that the Latin names for the species *Pinus*, *Picea* and *Abies* should be translated with 'pijn', 'den' and 'spar', in stead of the customary Dutch names 'den', 'spar' and 'zilver-spar'. Not only will the 'pijnboom' regain its legitimate place in the Dutch flora, but Dutch children can sing 'oh, denneboom' without the problem that the first tree name that they learn unintentionally is incorrect.
11. The alcohol consumption per capita in the Netherlands is presently fivefold regarding the consumption in the 1950's. These figures can be obtained from the official sales records, but also deduced from the design of road plans of modern suburbs.
12. After the submission of a manuscript to a scientific journal for a peer review the author often feels himself like a pinball, while anonymous colleagues push the buttons like mad.
13. The strip of paper on the backside of a credit card where the signature of the bearer should be placed is much too small, which often leads to a total mutilation of the bearer's signature, and, in turn, leads to problems with identification.
14. A hedge between keeps friendship green.

Paul Kiepe

'No Runoff, No Soil Loss: soil and water conservation in hedgerow barrier systems'.
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Paul Kiepe

**No Runoff, No Soil Loss:
soil and water conservation
in hedgerow barrier systems**

Proefschrift

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in de landbouw- en milieuwetenschappen
op gezag van de rector magnificus,
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in het openbaar te verdedigen
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Trefw.: bodem- en waterconservering, erosiebestrijding, *Cassia siamea*, Kenia.

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Chapter 3:

Kiepe, P., 1995. Cover and barrier effect of *Cassia siamea* hedgerows on soil conservation in semi-arid Kenya. Submitted to Soil Technology.

Chapter 4:

Kiepe, P., 1995. Effect of *Cassia siamea* hedgerow barriers on soil physical properties. Geoderma, 66: 113-120.

Chapter 5:

Kiepe, P., 1995. Soil water status beneath *Senna siamea* hedgerow barrier systems after rain storms. Submitted to Plant and Soil.

Chapter 9:

Kiepe, P. and Stroosnijder, L., 1995. Principles of modelling soil and water conservation in hedgerow barrier systems. Submitted to Modeling Geo-Biosphere Processes.

Chapter 10:

Kiepe, P., 1995. Applications of modelling soil and water conservation in hedgerow barrier systems. Submitted to Modeling Geo-Biosphere Processes.

Abstract

Kiepe, P., 1995. No runoff, no soil loss: soil and water conservation in hedgerow barrier systems. Doctoral thesis, Agricultural University, Wageningen, The Netherlands, xii + 156 p., 20 tables, 35 figures, 4 annexes, with English and Dutch summaries. Also published in the series Tropical Resource Management Papers. ISSN 0926-9495.

Land degradation by water erosion represents a serious, and fast increasing, environmental threat. Hedgerow barriers control water erosion through the presence of the tree stem and through an increase in infiltration beneath the hedgerow. The infiltration rate beneath hedgerows is 3-8 times higher than in the alley where crops are grown. Soil water content measurements in hedgerow barrier systems indicate that infiltrated water penetrates the soil beneath hedgerows deeper than the soil beneath the alley and the control. An analytical framework for calculating the impact of hedgerows and mulch on infiltration, runoff and soil loss is presented here. The framework was expanded with algorithms to calculate the impact of hedgerows of various densities, ranging from 1-4 rows. The framework was applied on a seasonal basis and the predictions were satisfactory. Extreme events can be explained when dynamic soil and plant conditions are incorporated. A dynamic simulation model called SHIELD has been developed that explains the experimental observations for runoff, soil loss and crop yields using daily time steps. Application of the model illustrates the importance of dynamic soil and plant conditions to the amount of soil being lost and shows that SHIELD can be used to compute the maximum desired distance between hedgerows with respect to tolerable soil loss.

Additional keywords: agroforestry, erosion, infiltration, *Cassia siamea*, maize, Kenya, simulation model.

'A nation that destroys its soils, destroys itself.'

F.D. Roosevelt, 1937. Letter from President to Govenors. White House, Washington, D.C.

'The power of the simulation approach is that it can approve an essentially continuous monitoring of the entire system as it varies in response to any number of factors on the basis of cause-and-effect mechanisms. However, the predictions obtained must be validated experimentally before they can be applied with a sufficient degree of confidence.'

D. Hillel, 1980. Applications of Soil Physics. Academic Press, New York.

Preface

Research and ideas that are found in this thesis are based on my work at the International Centre for Research in Agroforestry (ICRAF), where I was assigned by the Directorate-General for International Cooperation of the Netherlands Government (DGIS) from October 1987 until November 1992. When I joined ICRAF the C in the acronym stood for Council and not yet for (CGIAR) Centre. The donor community expected from ICRAF at the time to collect, digest and disseminate information on agroforestry and indicate potential research areas to other institutes, while ICRAF was only allowed to undertake research in the so-called 'Collaborative Programme'. My work at ICRAF was to support ICRAF in solving problems related to soil science, in the most general sense, and to undertake field work to demonstrate the potential of agroforestry as an environmentally-sound land-use system and to locate possible knowledge gaps. In Machakos, where I was expected to do my field work, four agroforestry technologies related to soil and water conservation were already demonstrated. Based on an evaluation of these demonstrations one agroforestry technology evolved as the most promising one and was subsequently planted in additional trials in order to get more information on its functioning. After three years at ICRAF it occurred to me that the data that I had collected from the runoff plots was of such great value that it could be used for a Ph.D. thesis, despite the fact that one trial was not replicated and two were replicated twice. However, some crucial treatments were common in two or more experiments, so there was a check on the accuracy of the data. Together with the initial measurements that indicated a low variability in runoff and soil loss the reliability of the data was ensured.

During the summer of 1991 I started my Ph.D.-work with a modelling course at Wageningen Agricultural University in the Department of Irrigation and Soil and Water Conservation. Usually, Ph.D. students at Wageningen start with a literature review and develop a model simultaneously. Then, the research agenda is set with the help of the model. In my case, all trials were planted and measurements were running. However, the model that I developed in the summer of 1991 indicated a lack of some crucial data. Fortunately, I had still more than a year left to measure the required soil physical data and to collect more runoff and soil loss data. The new approach forced me to analyze my data again, but in a different way, after I had left ICRAF by the end of 1992. Additionally, measurements were carried out in the Soil Physics Laboratory in the spring of 1993.

Physical soil and water conservation studies can be divided into three groups. The first group can be characterized by reporting runoff and soil loss from various systems, proving that some systems are better than other systems, but without explaining why certain systems differ in the ability to control erosion. Most accounts about the conservation potential of agroforestry systems fall into this group. The second group reports about long-term seasonal averages, but neglects extreme events. Most accounts about soil conservation modelling fall into this group. Finally, the third group concentrates exclusively on modelling of extreme events. Most of the hydrological modelling of runoff events, sometimes with soil loss included, falls into this last group. These different approaches are seldom combined, though it is recognised that in addition to seasonal runoff and soil loss in a number of cases extreme events are causing the major part of soil loss. This study is an attempt to explain runoff and soil loss on a seasonal basis including extreme events.

The framework and the model that I developed in Wageningen are based on 52 plot years (or 104 cropping seasons) of runoff measurements. From my point of view it is a quite lot of data that was collected in such a short time, but it cannot match the 12,000 plot years used in the USA to model soil loss. Still, I do not have the time to wait for 900 years of data collection and, moreover, I am convinced that a combination of a modelling approach and corresponding experimental data is worth to be published.

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1 Introduction to hedgerow barrier systems

1.1 General introduction

Soil is the single most important non-renewable resource for farming in the tropics. Over the last 45 years, one third ($2.0 \cdot 10^9$ ha) of the total arable land in the world has suffered from land degradation through acidification, compaction, contamination, salinization, wind erosion, but mainly through water erosion ($1.1 \cdot 10^9$ ha). The greater part of the degraded lands cannot be restored by regular farm operations, while $0.3 \cdot 10^9$ ha cannot be restored at all because of the high costs involved (Parlevliet, 1993). Population pressure and a paucity of level land forces people to farm ever steeper slopes. Farming operations that are not intrinsically environmentally harmful on level land can be disastrous on slopes. For instance, soil loss from traditionally cultivated cassava fields was $3 \text{ t ha}^{-1} \text{ y}^{-1}$ on flat land and $221 \text{ t ha}^{-1} \text{ y}^{-1}$ on a 12% slope (Aina et al., 1977). It makes sound economic sense to invest in soil and water conservation projects when costs of soil loss, land degradation and off-site effects are considered (Pimentel et al., 1995). In general, crops present serious problems when cultivated on slopes and trees do not, a fact which points to the potential benefits of using a combination of the two (Young, 1986). A suitable option is the use of hedgerow barriers to control water erosion on slopes, the subject of this thesis. The research emphasis on water, the choice of on-station research as well as the choice of the selected hedgerow species will be explained in Chapter 1. The issue of conflicting reports on the performance of hedgerows is discussed next, in Chapter 2, while the conservation capability of hedgerow barrier systems is demonstrated in Chapter 3. Chapter 4 describes the crucial water-flow process that affects runoff, which is infiltration. The subsequent water status of the soil beneath hedgerow barrier systems, which becomes crucial in the case of low subsoil permeability, is described in Chapter 5. The analytical framework for runoff and soil loss estimations from hedgerow barrier systems is discussed in chapters 6, 7 and 8, where it is applied on a seasonal basis. This framework is subsequently used on an event basis in a dynamic process-based simulation model, which is the subject of chapters 9 and 10. The purpose of the simulation model is to support calculations on the optimum design of hedgerow barrier systems from a soil and water conservation perspective.

1.2 No runoff, no soil loss

This study focuses on the role of water in soil erosion and the effect of runoff on soil loss. There are three main reasons for concentrating on water in the analysis of the erosion process. First, water is the eroding agent, and second, water is the transporting agent for dislodged soil particles and plant nutrients. The third reason is that water is often a limiting factor in plant production systems in semi-arid areas. The introduction of hedgerows in between crops will augment the competitive pressure on an already scarce resource. The balance between the water conservation aspect of hedgerows planted on slopes and their water consumption is, therefore, also important.

The inception of soil loss due to water erosion commences when a drop of water hits the soil surface. This process, where soil particles are dislodged from the matrix, is called splash erosion or detachment. On level land the particles will shift over small distances but will not be carried away. The net effect of these local displacements will be zero, but it does not mean that this process is not harmful. Although there is no soil loss, the soil surface may well be damaged by this process. Slaking, crust formation, surface sealing and compaction are often the result. On a slope there will be a net effect of particles moving down the hill. Due to the force of gravity, the particles on the downward side will be launched farther away than the particles on the upper side (Ellison, 1944; 1947b).

When overland flow occurs on slopes it carries away the separated soil particles, a process often more important than the gravitation process. The soil particles may be deposited temporarily on the way downhill and lifted again by rainfall impact, so-called redetachment (Rose, 1993). This process is known as sheet erosion. A very thin layer of overland flow, together with rain splash, can cause tremendous soil loss. Sheet erosion is not conspicuous on the land itself. The colour of the water in streams and rivers after a rain storm is the most noticeable form of evidence of sheet erosion. Such erosion is known as the off-site effect of soil erosion and it can influence a whole nation. Primary rivers flow into bigger rivers and discharge increases. The navigability of waterways decreases and nautical traffic is hindered because of shallower water. Not only the discharge increases, but also the momentum of storm floods increases because of the increased density of the river water. These storm floods damage or undermine river banks, bridges, roads and other constructions and are a potential hazard for human lives. Large reservoirs for hydro-electric power face the same problem of siltation as the small irrigation dams. In addition, a high silt content in the water of the reservoir decreases the visibility of the water and has a detrimental effect on fish stocks. The greatest single pollutant of surface water in the USA on a volume basis is soil sediment (Batie, 1983). Kenya has become aware, for instance, that the Tana River deposits so much sediment on the coral reef just offshore in the Indian Ocean that these deposits form a major threat to the marine ecology of that area. The source of the sediments are the intensively cropped slopes of Mount Kenya, about 500 km upstream.

When overland flow concentrates in rills, erosion becomes more obvious. These little streams carry away sediments that were detached by rainfall, while the water flow can develop enough momentum to dislodge soil particles itself. The latter process is known as entrainment or rill erosion (Ellison, 1947a; Meyer & Wischmeier, 1969; Rose, 1993). While sheet erosion is a slow but continuous process, rill erosion can abruptly exacerbate the problem. When rills concentrate in bigger streams, gully erosion starts, which is the most overwhelming of all erosion processes. Like a soil-chewing monster, the gully will enlarge itself every time there is a rainstorm, when the head of the gully will eat its way upstream, feasting on the farmers' land. Gullies are spectacular and a well-known feature. In the old days soil conservation was synonymous with gully control using check dams and gabions. But the origin of any gully is splash and sheet erosion, hidden to the layman's eye. It is there where water erosion starts and it is there where it should be controlled, splash erosion by soil cover and sheet erosion by barriers to avoid the runoff concentrating in rills. It is the runoff that should be controlled or arrested, right where it starts: on the farmers' fields.

1.3 On-farm versus on-station

Tackling the problem of soil erosion from farmers fields does not necessarily mean that the study has to be undertaken on-farm. Of course, the validity of results obtained in a well-managed research station cannot be compared with the reality of farmer-managed fields. However, it does not mean that all on-station research has to be abandoned. A research station is nothing more than - and should be treated as - an outdoor laboratory. It is bad practice to take laboratory results straight to the user. Indeed, some research will never take place on-farm because it takes a small army of skilled workers to carry out measurements or because precious equipment is involved. This is especially the case, when the experiments are designed to get a better understanding of a system's behaviour. On the other hand, when improved planting material is tested or novel farm operations or new management techniques are tried out there is little doubt that it should happen on-farm. However, this kind of research is more applied, like the evaluation of the adoptability of hedgerow barriers in farming systems (Fujisaka, 1989; 1993; Wiersum, 1994), which is quite different from research into the basic flow processes in hedgerow barrier systems. Therefore, two main reasons can be given for investigating this topic on station:

- a) This study was proposed to clarify processes involved in the soil and water conserving potential of hedgerow barriers, with and without mulch. As the emphasis is on understanding the system by studying the various components and processes of the system it is obvious that the experimental treatments do not represent optimal or even sensible agroforestry systems for land users. As soon as enough knowledge is gathered on how the systems operate, a suitable system can be designed for farmers. This prototype can be taken onto a farm and subsequently tested. It is not advisable to start testing systems on a farm without any degree of confidence in the design.
- b) Soil erosion measurement techniques for on-farm research are often qualitative and sometimes quantitative, although not very accurate or precise in this respect. Until now the only measurement technique that provides reliable information is large runoff plots with wash traps and collection tanks. Detailed monitoring of runoff and soil loss requires a large financial input plus a large number of skilled workers. This workforce may have to come into action for only a number of days per year, but they have to be on stand-by every day.

1.4 Hedgerow technologies

The use of hedgerows is conspicuous in three agroforestry technologies: boundary planting, hedgerow intercropping and hedgerow barriers. Boundary planting is the most common one, where hedgerows are used as fences to keep animals in or out, or as property demarcation. It is distinctly different from the other two hedgerow technologies, which are often confused because the appearance of more or less parallel-running hedgerows is almost identical. Although there are many similarities between the hedgerow barrier technology and hedgerow intercropping there is one important distinction. In hedgerow intercropping or alley cropping the planting distance of trees within the row is usually 0.5-1.0 m, or sometimes more. The biomass production of the tree is optimized to be incorporated in the soil in an attempt to

restore soil fertility and also to provide staking material, firewood and fodder (Kang et al., 1981). However, in the hedgerow barrier technology trees should be planted close together (0.2-0.3 m) to function as erosion barrier. In hedgerow intercropping tree biomass production is the aim, while in the hedgerow barrier technology soil and water conservation is the aim and tree biomass is an auxiliary product, albeit an important one.

1.5 The choice of the hedgerow species

It is not surprising that a lot of attention in agroforestry research is on the quest for appropriate tree species, i.e. trees with low competitive potential and high value products (Wood & Burley, 1991). The careful scanning of opportunities will lead to the identification of species that best suit proposed agroforestry systems, first of all by identifying promising species and secondly by adjusting tree management in such a way that negative features will be diminished. For each different agroforestry technology a tree species has to fulfil a particular set of requirements, added to location-specific requirements. The hedgerow species to be selected for this study had to fulfil the following requirements. It had to be

- 1 a multi-purpose tree species: the tree should possess more than one economically useful product or service function that can be exploited. It is a management option that applies to all tree species used in agroforestry.
- 2 a deep-rooting tree species with a minimum of lateral roots to minimize below-ground competition.
- 3 a legume: any additional input of nitrogen is most welcome in any low-input cropping system.
- 4 non-competitive: although a fast growing species is preferred, the tree should not grow at the expense of the crop, because soil conservation is the aim of this study and tree biomass production of secondary importance.
- 5 easily coppiced: the tree had to undergo a twice yearly pruning regime.
- 6 able to provide a good surface mulch: leaves applied as mulch for soil protection should not decay too readily and, preferably, should possess resistance to termites.
- 7 tolerant of semi-arid conditions.
- 8 tolerant of a high altitude.

The first two requirements are central to all agroforestry technologies. Requirement 3, the additional input of nitrogen in low-input systems that are often low in nitrogen content is most welcome. However, any prominent advantage of the tree to the crop due to its nitrogen-fixing capability should not lead to a competitive advantage (requirement 4) in capturing other resources. If so, a severe pruning regime (requirement 5) can decrease the competitive advantage of the tree. Requirement 6 is specific to this study and was postulated to test the efficacy of tree mulch for soil protection. Requirements 7 and 8 are location specific. Ideally, for every location there should be a database or expert system listing a kind of suppression series of tree and crop species (e.g. Machakos, Kenya: *Leucaena leucocephala* > *Zea mays* = *Cassia siamea* > *Vigna unguiculata* > etc.). Equipped with such a list the interference between plants can be anticipated and the information can be used in the design procedure of the lay-out and management of the trees.

A species that fits most requirements for this study is cassia (*Cassia siamea*, Lam.), whose botanical name has recently changed to *Senna siamea*. Since it is known worldwide as cassia, this name will be used in this thesis. Cassia showed very few signs of competition in previous experiments in Machakos, and as this study is concerned with the soil and water conservation aspect of hedgerow barriers, a non-competitive hedgerow species is preferred. A peculiarity is that despite the absence of nodules, levels of N and P were relatively high in the soil beneath cassia in a comparative study. The levels were higher than the control, but also higher than the levels in the soil beneath nodulating leguminous trees (Yamoah et al., 1986). With respect to mulch quality, cassia leaves contain a high amount of tannin, which makes it suitable for soil protection. Cassia was used in all treatments and experiments, simply to allow for comparison between treatments without introducing an additional variable and not because it is the only species that fits the requirements. Therefore, cassia was also being used as fodder hedge, despite the fact that it is not recommended for that purpose because the feed quality is low and it is toxic to pigs (National Academy of Sciences, 1980).

2 Conservation versus competition: the pros and cons of planting hedgerow barriers for soil conservation

Abstract

Agroforestry systems are land-use systems focused on crop and tree production that often have soil conservation as an additional benefit. The hedgerow barrier technology is an agroforestry technology that is used specifically for soil conservation. Improved crop production and tree biomass are consequential products. Production increase of tree biomass in hedgerow barrier systems can be attained by using fast-growing species. These species put great demand on natural resources which may conflict with crop production. Careful selection of the appropriate tree species and subsequent management with respect to the aims of the land user will prevent such a conflict. To improve the design of hedgerow barrier systems, a more detailed knowledge of the soil and water conservation process is required.

2.1 Introduction

Agroforestry is a collective name for land-use systems where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately grown on the same land in association with agricultural crops, pastures or livestock, either in some form of spatial arrangement or temporal sequence, and in which there are both ecological and economical interactions between the different components (Lundgren & Nair, 1985). An agroforestry technology or practice is an arrangement of components in space and/or time, while an agroforestry system is a specific local example of a technology (Young, 1988). There are about twenty different agroforestry technologies and probably thousands of agroforestry systems (Young, 1989). Land users practice agroforestry with one or more objectives, ranging from profit maximization, risk spreading and maintenance of soil organic matter to prevention of erosion. Profit maximization comes from the auxiliary tree products, which may be for their own use, like fodder, or as marketable products, like fruit and timber. One can often distinguish between a user's goal (e.g. profit maximization) and a coincidental effect (e.g. soil and water conservation). From an economic perspective soil and water conservation is seldom the principle user's goal. Most agroforestry systems intrinsically protect the soil by either a succession of canopy layers or a litter layer (such as homegardens or multistorey tree gardens). However, some agroforestry systems are detrimental to the environment. These systems have some environmentally adverse land-use practices in common, like the selective removal of canopy layers, removal or burning of litter and clean-weeding. Examples of this type of system are shifting cultivation when practised by migrant farmers and systems geared towards commercial timber production. Both categories are reported to have substantial soil losses (Wiersum, 1984). Clearly, it is not the trees but the spatial arrangement of the trees that protects the soil against erosion (Wiersum, 1985).

2.2 Conservation through hedgerow barriers

The only agroforestry technology that focuses specifically on erosion control is the contour hedgerow or hedgerow barrier technology. Here, soil and water conservation is the priority next to crop production, while tree products such as fodder or stakes are considered auxiliary. For crop production on slopes this is the agroforestry technology that is most suitable for a wide range of environments. Furthermore, the implementation of the hedgerow barrier technology is quicker, less laborious and hence less costly than mechanical soil-conservation measures, such as digging ditches or terrace construction (Metzner, 1976; Hudson, 1992 Agustin & Nortcliff, 1994;). The gradual development of terraces in hedgerow barrier systems catches up with mechanically constructed terraces within 4-5 years (Fig. 2.1; Kiepe & Young, 1992). Therefore, there is no necessity to invest money and labour in terrace construction. For this reason these terraces are called *sengkedan kridit* in Indonesia or 'terraces for granted' (Schuitemaker, 1949).

The potential use of hedgerow barriers for soil conservation was advocated as early as the beginning of this century (Kerkhoven, 1913). There have been but a few scattered accounts since then of the use of hedgerow barriers (Coster, 1938; Schuitemaker, 1949). A renewed interest started around 1980. An extensive on-farm programme started in 1978 in the Philippines using leucaena (*Leucaena leucocephala*), *Leucaena diversifolia*, *Flemingia congesta*, *Desmodium rensonii*, calliandra (*Calliandra calothyrsus*) and gliricidia (*Gliricidia sepium*) (Tacio, 1993), while the first contemporary erosion study on hedgerow barriers was in Nigeria where leucaena and gliricidia were planted on a 7% slope in 1982 (Lal, 1988). Biomass from the hedges was spread on the alley and incorporated into the topsoil. Leucaena and gliricidia hedgerows reduced runoff to 10% and 13% respectively, and soil loss to 4% and 3%. In the Philippines, hedgerows of *Desmanthus virgatus* were planted on a 14-19%. Without mulch the hedgerows decreased runoff to 50% and soil loss to 33%, and with mulch application runoff to 22% and soil loss to 3% of the control (Paningbatan, 1990).

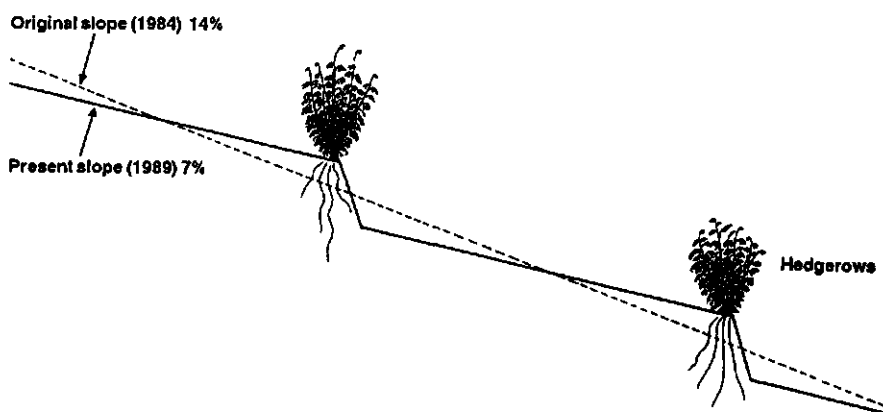


Fig. 2.1 Progressive terrace formation in hedgerow barrier systems.

In Rwanda, double-row hedges of calliandra were planted on a 28% slope and intercropped with cassava. Hedgerow prunings were applied as surface mulch on the alleys. The calliandra hedgerows reduced runoff to 33% and soil loss to 5% of the traditionally cropped cassava control (König, 1991). In Colombia, hedgerow barriers of gliricidia intercropped with maize on a 43% and a 75% slope were compared with traditional farming practices. Leaves of hedgerow prunings were used as mulch, while the woody parts were placed at the base of the hedges to reinforce the barrier. On the 43% slope the hedges reduced runoff to 55% and soil loss to 49%. On the 75% slope runoff was reduced to 49% and soil loss was reduced to 56% (Van Eijk-Bos & Moreno, 1986). In this last study trees were planted 0.50 m apart within the hedgerow. Obviously, the result would have been much better if the trees were planted closer together because the tree stems reduce the velocity of overland flow and prevent the chanelization of water (Stocking & Elwell, 1976). Accounts from large-scale implementations of hedgerow barriers on farms are positive but always descriptive. Yield increase and high adoption rates by farmers are reported from Indonesia on the islands of Java (Schuitemaker, 1949) and Flores (Metzner, 1976), from Mindanao in the Philippines (Tacio, 1993) and from Haiti (Pellek, 1992), while adoption of farmer-specific adapted hedgerows was reported from the Philippines (Fujisaka, 1993) and Indonesia (Wiersum, 1994).

2.3 Competition in hedgerow barrier systems

Introducing trees for soil conservation into an agricultural system equals the introduction of plant interference. All plant species demand basic resources for their growth and maintenance. In a monoculture each individual possesses more or less the same ability to capture resources, but in the case of two different species one species is often more apt in capturing a particular resource than the other (De Wit, 1960), especially, if one of the components is an annual and the other a perennial (Ong et al., 1991). If resources are abundant competition for water or nutrients will be insignificant, but agroforestry systems are usually implemented in marginal areas where at least one of the resources is limited.

Competition for light arises as soon as shading takes place. However, in a hedgerow barrier system the chances of shading becoming prominent are small because the hedges are deliberately pruned close to the ground (0.3 m). A tall-growing crop, like maize, does not suffer from light competition in hedgerow barrier systems as long as it keeps its vertical growth advantage. The species that is tallest in intercropping intercepts most of the solar radiation, while any increase in the leaf area index (LAI) of the overstorey implies a corresponding decrease in LAI of the understorey (Cannell, 1991). Short-staying crops, such as beans, suffer close to the hedge from some degree of light competition, but apart from a low pruning height for the hedgerow, frequent pruning will also diminish light competition. Competition in hedgerow barrier systems is, therefore, predominantly confined to below-ground competition for water and nutrients.

Hedgerow barriers control erosion mainly through increasing the infiltration (cf. Chapter 4). Frequent pruning stimulates dieback in part of the root system, which will in turn increase the chances of a higher permeability of the soil beneath the hedgerow (Van Noordwijk, 1991b). It means that less water will run off, but it does not automatically mean that more

water will be available for the crop. The trees that are utilized to decrease runoff need at least some of the extra infiltrated water for their transpiration. The introduction of plants to increase infiltration means that the system as a whole is conserving water, but, if the extra water is meant for the crop, a tree species needs to be selected that conserves more water than it uses for its own maintenance and growth.

Besides competition for water, below-ground competition also comprises nutrient competition. Below-ground competition is closely linked to the distribution of both tree and crop roots. The root systems of seventy tropical tree species, mostly legumes, were classified by Coster (1932) and three major groups could be distinguished: deep-rooting trees, shallow-rooting trees and trees that are a combination of both. It appeared that all fast-growing species had either a shallow rooting system or a tap root in combination with many lateral roots. All deep-rooting species without lateral roots were slow-growing. Therefore, if competition is to be minimized deep-rooting species should be selected. But even then, deep-rooting trees always have some lateral roots and severe pruning stimulates the growth of superficial lateral roots (Van Noordwijk et al., 1991a). Care must be taken that the effort to reduce above-ground competition should not lead to an increase in below-ground competition.

2.4 Conservation versus competition

Crops grown in agroforestry systems may benefit from conservation but may suffer from competition. The degree of competition depends on the tree species, the environmental conditions and the layout. Although the hedgerow barrier system focuses on soil conservation and crop production, the relative importance of the auxiliary benefits of hedgerows should be taken into account. Tree prunings can be used as mulch or as tree fodder, but not for both at the same time. The required chemical composition differs considerably for mulch and fodder. In the case of mulch, the protection of the soil surface against splash erosion should last as long as possible, preferably to the end of the rainy season. Therefore, the selected species should have slow-decomposing leaves that should not be palatable to termites or other faunal species. The rate of decomposition depends on the ratio between polyphenolics and nitrogen (Palm & Sanchez, 1991), as well as temperature and humidity. Therefore, a species that is suitable for mulch should have rather big leaves that contain high contents of slow-degradable substances such as lignin, tannin or polyphenolics.

The leaves of some tree species may contain remarkably high rates of digestible crude protein. Prunings of trees such as *leucaena* are considered to be good fodder and are reported to contain more than 20% digestible crude protein (Reynolds & Atta-Krah, 1989). Furthermore, hedgerow biomass is available throughout the year, which is an attractive condition for the availability of animal feed in the dry seasons in semi-arid areas. Particularly in mixed farming systems, livestock can be fed with fodder pruned from the hedgerows. For instance, hedgerow intercropping with small ruminants increased economic returns by 30% in one particular study (Jabbar et al., 1994). However, opting for a fodder hedge in a soil conservation system means that the system has to rely entirely on the hedgerow in its capability as erosion barrier, and lacks soil protection from a mulch cover.

Conflicts arise either when people want the best of both worlds, high crop yields and a high tree biomass production, or when tree species are planted that are not suitable for that particular environment. Fast-growing trees use a lot of resources and are likely to compete with crops. However, the amount of tree biomass may partly or totally compensate the loss of crop yield when the fodder value balances crop returns. A negative ecological interaction does not necessarily mean a negative economic response. A yield reduction of 25-35% in a leucaena hedgerow intercropping system in India showed twice the gross returns from sole cropping (Singh et al., 1989).

Examples of the uncontrolled copying of agroforestry systems from one agro-ecological zone to another without considering the climatic and edaphic requirements are many. Care should be taken that the failure of an agroforestry system in a particular environment should not lead to declaring the entire technology inept. In the past, most hedgerow barrier systems were used in the humid tropics, although the technology has already been used successfully in a rain-shadow area on Flores (Metzner, 1976). Therefore, the tree species selected for a hedgerow barrier system in a semi-arid environment should not require large amounts of water, or, if it does, should provide sufficient economic benefits in return.

2.5 Conclusion

For a hedgerow barrier system to be successful, the increase in available resources for the crop should outweigh the possible losses on the side of competition. Increased infiltration, input of organic matter through mulch and fine-root turnover, plus the soil and nutrients retained by the hedge, are one part of the story. The other part is the selection of the appropriate tree species. Two hedgerow barrier ideotypes can be defined, depending on the use of the tree biomass opted for; mulch or fodder. Both types have the following five characteristics in common: multi-purpose, deep-rooting, leguminous, non-competitive and are easily coppiced (cf. requirements 1-5, Chapter 1). The difference between the two ideotypes is caused by the preference of the land user for a mulch or fodder species. If the prunings are to be used as surface mulch the leaves should not readily decompose, but if the prunings are to be used as fodder the leaves should contain a high content of digestible crude protein. Additional requirements can be made depending on climatic and edaphic factors. An extensive list of tree species used as hedgerows in the tropics was prepared by Kuchelmeister (1989).

A better understanding of the functioning of the hedgerow barrier system is indispensable in order to minimize competition without affecting the conservation capacity. Therefore, in-depth research into changes in infiltration under hedgerows as well as under the alley, and the subsequent internal drainage, needs to be undertaken. Preferential-flow paths need to be detected and quantified in order to gain knowledge for optimizing the layout of the system. The contact-area between the tree and the crop may be reduced to curtail competition. This can be achieved by increasing the distance between hedgerows, while simultaneously increasing the hedgerow density by planting double or triple tree rows. In addition, the potential of the hedgerows to function as a barrier to runoff, i.e. without the aid of tree prunings used as a surface mulch, offers scope for increasing the overall benefits. Therefore, it is imperative to quantify the role of the hedge and the mulch in soil and water conservation

separately so that the increased erosion risk of a cut-and-carry fodder system can be quantified, especially because stall-feeding in mixed-farming systems is presently taking off in many countries in the tropics.

3 Cover and barrier effect of *Cassia siamea* hedgerows on soil conservation in semi-arid Kenya

Abstract

The contribution of *Cassia siamea* hedgerows and mulch to erosion control was evaluated on a 14% slope of a Lixisol/Alfisol at Machakos, Kenya. The four treatments, in 400 m² runoff-plots were: hedgerows with prunings applied as mulch to the crop, hedgerows and crops with prunings removed, mulch only applied to the crop and a control. The hedgerows were planted on the contour, 4 m apart and 0.25 m between plants. Maize and cowpea were planted in sequence. The control plot sustained an average annual water loss over 3 years of 31 mm runoff and soil loss of 19 t ha⁻¹. The best treatment, hedgerows with mulch, reduced losses to 13% and 2% of the control. Hedgerows without mulch reduced losses respectively to 23% and 7%, while mulch without hedgerows reduced losses to 41 and 17%. Soil loss was considerably influenced by one single storm in April 1990 due to the nature of that storm and to the susceptibility of the soil to erosion at that particular time. Differences in crop yield between treatments were small. The hedgerow treatments depressed cowpea yield slightly in less than normal rainy seasons but improved cowpea yields in wet seasons.

3.1 Introduction

At the beginning of this century hedgerows of leguminous trees were advocated for soil conservation (Kerkhoven, 1913). Hedgerow barriers, planted on the contour in 1908 in a teak plantation in Java, Indonesia, demonstrated quantitatively the efficacy of hedgerows for soil conservation (Coster, 1938). The first contemporary research into the conservation potential of hedgerow barriers came from Nigeria (Lal, 1988) and successively from other parts of the humid tropics, e.g. Colombia (Van Eijk-Bos & Moreno, 1986), the Philippines (Paningbatan, 1990) and Rwanda (König, 1991). Hedgerow barriers were shown to be a suitable alternative for soil conservation in semi-arid areas too (Kiepe & Young, 1992).

Hedgerows of leguminous trees are also acclaimed for fodder production because the biomass of many species contains considerable levels of digestible crude protein (Brewbaker, 1989). Furthermore, tree biomass is available throughout the year which is especially appropriate for semi-arid areas where there is often a fodder shortage towards the end of the dry season. The use of tree biomass as mulch for soil protection and protein-rich fodder conflicts if the supply is limited. If biomass is taken away for animal feed, it cannot be used for soil protection. It is, therefore, meaningful to examine the conservation potential of hedgerows with and without mulch, in order to check if the system still effectively controls erosion when the prunings are taken away. Additionally, analysis of crop and hedgerow biomass yields should be included because it is imperative that a potentially-successful soil-conservation technology should keep crop yields at profitable levels.

3.2 Materials and methods

3.2.1 The study area

The experiment was established at the ICRAF Research Station in Machakos, Kenya (1° 33'S, 37° 14'E) at an altitude of 1600 m on a sandy clay loam over sandy clay developed in situ on rocks of the Precambrian Basement Complex. The soil is about 150 cm deep and classified as Chromic Luvisol (Kibe et al., 1981), revised by the author as Haplic Lixisol (FAO, 1988) or Kanhaplic Rhodustalf (Soil Survey Staff, 1990). Lixisols are prone to slaking and erosion, due to a low structure stability. This risk is enhanced by low subsoil permeability. Recommended land use for Lixisols is extensive grazing or forestry to avoid serious soil deterioration and water erosion (Driessen and Dudal, 1989). Rainfall distribution in Machakos is bimodal and there is a large variability in annual and seasonal rainfall, and in rainfall reliability (Braun, 1977). Locally, the rainy seasons are called the long and the short rains although both seasons qualify as short. The long rains (LR) usually start in the second half of March, last through May and have an average rainfall of 330 mm (\pm 155). The short rains (SR) start at the end of October and continue until January with an average rainfall of 365 mm (\pm 125). Another 65 mm (\pm 50) is falling in scattered showers off-season.

3.2.2 Experimental details

Four runoff plots of 10 x 40 m were installed on a 14% slope, each confined by a metal strip 0.3 m high that was placed across the top of the plot and down the sides to avoid cross flow. Runoff was intercepted by wash traps at the bottom of each plot and channelled through drain pipes into collection tanks. Runoff and soil loss were measured every time after an erosion event occurred. Measurements commenced in March 1990 and are still being continued. Rainfall intensity was measured with a tipping-bucket raingauge and spatial variability within storms was measured with a string of seven standard-WMO 0.127 m raingauges across the plots and linked to two standard-WMO 0.203 m raingauges. After one season of trial runs (SR 1989) runoff of three consecutive storms was measured before mulch was applied allowing for a comparison of the variability between the two plots without hedgerows and between the two plots with hedgerows. The coefficient of variation for runoff was 3% for both combinations, indicating a low spatial variability.

Four treatments were planted in each of the runoff plots of which two with hedgerow barriers. In treatment 1, hedge-with-mulch, prunings were applied on the alleys as surface mulch. In treatment 2, the fodder hedge, tree biomass was carried away. Treatment 3, the mulch treatment, received a seasonal application of surface mulch of the same quantity as treatment 1, but here from outside the plot. Treatment 4, the control, did not have hedgerows or mulch application.

Land and crop management were the same for all treatments. Hedgerows of cassia (*Cassia siamea*, Lam.), a non-nodulating leguminous tree, were planted on the contour in 1988. Trees were planted 0.25 m apart within-row and the distance between rows was 4.0 m. Two crops, maize (*Zea mays*, cv. Katumani Composite B) and cowpea (*Vigna unguiculata*, cv.

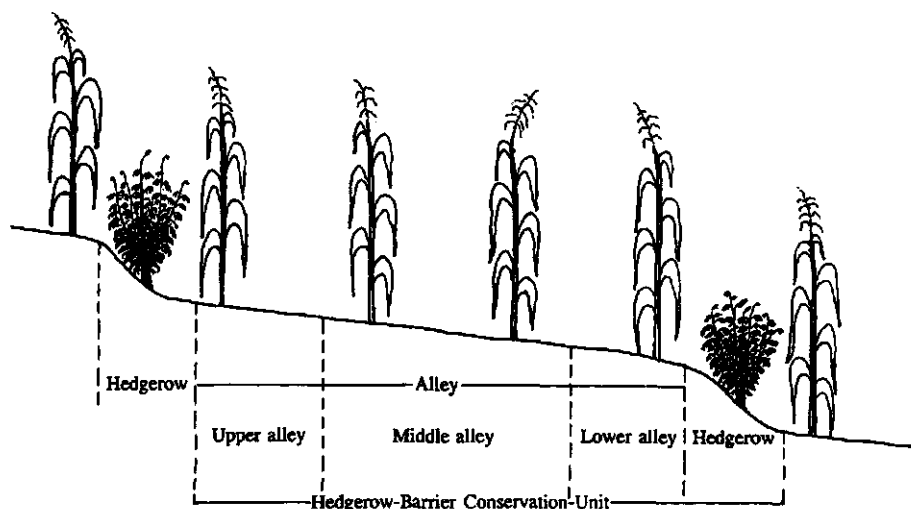


Fig. 3.1 Schematic cross-section through the hedgerow barrier system. Note that the hedgerows are added to the cropping system and do not replace any intended crop rows.

K 80), were grown in sequence from October 1988 onwards. The maize was planted in rows, 1.0 m apart (Fig. 3.1). The cowpea was grown in rows 0.6 m apart sacrificed 10% of its area. Yields reported below include the hedgerow areas. Maize received 40 kg of N and 40 kg of P_2O_5 ; cowpea was not fertilized. All plots were hand-hoed before the onset of the rains and weeds were removed by hand-hoe about six weeks after planting. Hedgerows were pruned for the first time in March 1989, afterwards every season before the onset of the rains.

3.3 Results

The seasonal erosivity index from 1984 to 1992 of the long rains (LR) was sixty percent higher than that of the short rains (SR): 186 versus 117 $t\ ha^{-1}\ h^{-1}$ (Table 3.1). The total number of storms was equally divided over both rainy seasons, 85 in the short rains against 86 in the long rains, indicating that storms in the long rains were more aggressive. The erosivity index EI_{30} ($t\ ha^{-1}\ h^{-1}$) (Wischmeier & Smith, 1978) is the sum of the products of total kinetic energy (E in $t\ ha^{-1}\ cm^{-1}$) and the maximum rainfall intensity recorded in any 30 minute interval (I_{30} in $cm\ h^{-1}$) for every storm. The kinetic energy (E) appeared closely related to storm depth (A in mm) (Fig. 3.2). Calculation of kinetic energy was replaced in Machakos by measuring A and converting it to E .

The runoff-measurement period of six seasons received 96 storms. On five occasions difficulties in runoff measurement were encountered. Once, rainfall was not uniformly distributed over the plots. The control plot received 16.9 mm while the other treatments received 26.8 mm. As well as this anomaly, overflow of the collection tanks of the control

Table 3.1 Seasonal and annual erosivity (EI_{30}) in $t\ ha^{-1}\ h^{-1}$ of Machakos Research Station for eight agricultural years (1 October 1984 to 30 September 1992).

Agric. Year	Short Rains	Long Rains	Annual Total
1984-1985	143.7	539.2	682.9
1985-1986	116.1	133.2	249.3
1986-1987	104.7	69.9	174.6
1987-1988	174.9	193.1	368.0
1988-1989	83.4	114.8	198.2
1989-1990	131.7	340.4	472.1
1990-1991	81.8	22.1	103.9
1991-1992	100.1	73.1	173.2
Mean	117.0	185.7	302.8

plot occurred three times in the last season that was exceptionally wet and which received 145% more than average. Despite these problems runoff and soil loss data were incorporated in the analysis. The fifth occasion was on 14 April 1990 (Fig. 3.3) when a major storm filled up the collection tanks of the control plot, blocked the system and covered the traps with

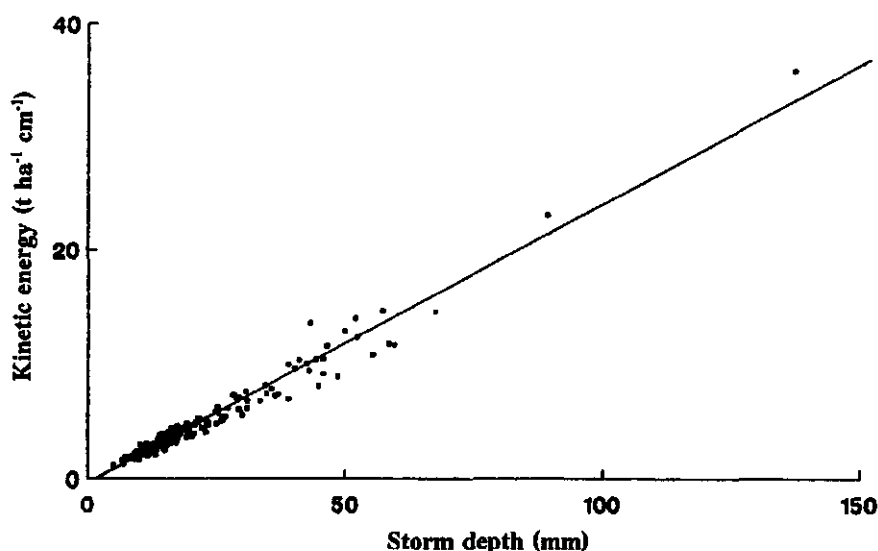


Fig. 3.2 Linear regression of kinetic energy (E in $t\ ha^{-1}\ cm^{-1}$) on storm depth (A in mm); $E = 0.243 A - 0.458$ ($n = 171$, $R^2 = 0.963$).

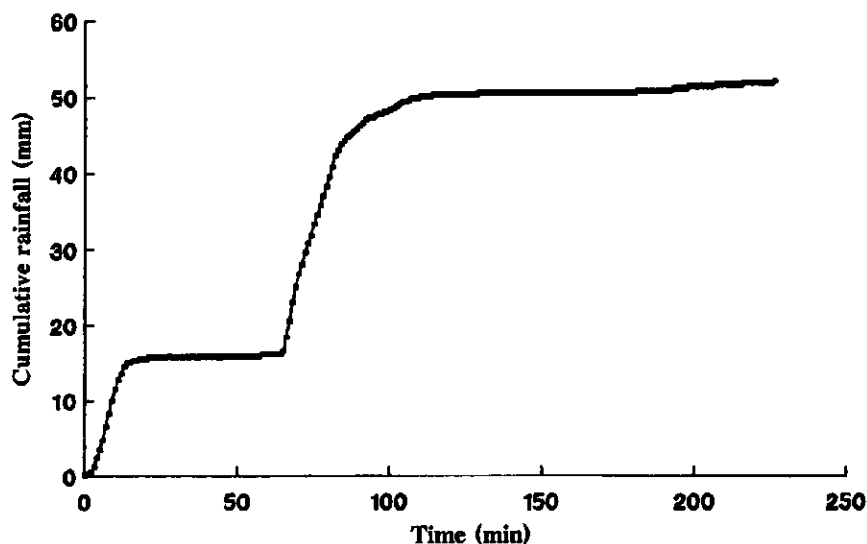


Fig. 3.3 Rainfall intensity of a major storm on 14 April 1990 represented as cumulative rainfall (P_{cum} in mm) over time (t in min).

sediments. The greater part of the sediment yield (34.3 t ha^{-1}) could be recovered, but virtually all runoff was lost.

Hedgerows were more effective than mulch in controlling runoff (Table 3.2) and soil loss (Table 3.3). Mulch reduced runoff to 41%, hedgerows to 23%, while their combination

Table 3.2 Runoff in mm over six seasons at Machakos Research Station.

Season	Rain (mm)	Control	Mulch-only	Hedge-only	Hedge + Mulch
LR 1990	631	3.2 ¹	2.5	1.3	0.8
SR 1990	333	1.0	0.6	0.4	0.5
LR 1991	214	1.7	0.4	0.2	0.2
SR 1991	352	13.0	4.0	0.9	0.4
LR 1992	222	11.2	0.7	0.7	0.4
SR 1992	808	64.1	30.5	17.8	9.5
Ann. Mean	853	31.4	12.9	7.1	3.9

¹ Runoff from 14 April 1990 was lost, so the data of that storm are not incorporated.

Table 3.3 *Soil loss in t ha⁻¹ over six seasons at Machakos Research Station.*

Season	Rain (mm)	Control	Mulch-only	Hedge-only	Hedge + Mulch
LR 1990	631	36.1	4.6	2.2	0.2
SR 1990	333	0.0	0.0	0.0	0.0
LR 1991	214	0.0	0.0	0.0	0.0
SR 1991	352	5.4	1.1	0.0	0.0
LR 1992	222	3.8	0.0	0.0	0.0
SR 1992	808	12.6	4.1	1.6	1.2
Ann. Mean	853	19.3	3.3	1.3	0.5

reduced runoff to 13% of that recorded in the control. Mulch reduced soil loss to 17%, hedgerows to 7% and their combination reduced soil loss to 2% of that recorded in the control. When rainfall was high crop yields were better in the mulch and hedgerows treatments (Tables 3.4 and 3.5), but when rainfall was below average cowpea yield was reduced by 27-33% (LR 1991) due to water competition, while maize was not affected (LR 1992). On the other hand, when rainfall was high cowpea was protected from runoff by the hedgerows resulting in 17-200% higher yield than the control, where plants were damaged by runoff (LR 1990) or subject to root and collar rot (SR 1992). Cowpea yields were also adversely affected by runoff on the mulch plots, but to a lesser extent than on the control. In the remaining season (LR 1991) cowpea yield was highest in the mulch treatment, while maize yield was consistently the highest in the mulch treatment. There was no significant difference in yield of the hedgerow prunings (Table 3.6). The CV-values in table 4, 5 and 6 indicate the within-plot variability, that was derived from comparison of the yields per alley.

Table 3.4 *Oven-dry grain yields of cowpea in t ha⁻¹ in Cassia siamea hedgerow trials with and without mulch, cassia mulch only and a crop-control at Machakos Research Station.*

Season	Rain (mm)	Control	Mulch-only	Hedge-only	Hedge + Mulch
LR 1989	330	0.83	0.88	0.89	0.83
LR 1990	631	0.15	0.26	0.37	0.46
LR 1991	214	0.52	0.59	0.35	0.38
SR 1992	808	0.29	0.38	0.34	0.41
Mean	496	0.45	0.53	0.49	0.52
CV (%)		8	10	18	11

Table 3.5 *Oven-dry grain yields of maize in t ha⁻¹ in Cassia siamea hedgerow trials with and without mulch, cassia mulch only and a crop-control at Machakos Research Station.*

Season	Rain (mm)	Control	Mulch-only	Hedge-only	Hedge + Mulch
SR 1989	441	2.67	3.20	2.97	3.14
SR 1990	333	2.20	2.94	2.39	2.38
SR 1991	352	1.93	2.16	1.83	1.91
LR 1992	222	1.51	1.72	1.43	1.54
Mean	337	2.08	2.50	2.16	2.24
CV (%)		6	7	7	10

3.4 Discussion

Soil erosion in arid and semi-arid areas is characterised by major events with a recurrence interval (RI) of several years and little erosion in between. Such a major event occurred in Machakos on 14 April 1990. Calculation of the RI by ranking (Chow, 1964) raised a few questions. Usually, the RI of the total amount of daily rainfall (P_d) is calculated, because this data is easy to acquire. However, it is not yet clear which storm characteristic, or which combination of storm characteristics, is a reliable indicator for the initiation of soil erosion.

Table 3.6 *Biomass yield of Cassia siamea prunings in t ha⁻¹ over eight seasons at Machakos.*

Season	Rain (mm)	Hedge-only	Hedge + Mulch
LR 1989	330	1.43	1.44
SR 1989	441	1.91	2.08
LR 1990 ²	631	1.22	1.09
SR 1990	333	1.34	1.32
LR 1991	214	0.84	0.82
SR 1991	352	1.66	1.60
LR 1992	222	0.80	0.80
SR 1992	808	1.72	1.59
Ann. Mean	833	2.73	2.68
CV (%)		16	17

² The cassia hedgerow was pruned twice this season to which it did not respond well.

First, because the relationship between storm characteristics is not constant and the RI may substantially differ for each characteristic (Wischmeier, 1962). Secondly, storm characteristics indicate the potential danger of a storm. The actual occurrence of large amounts of soil loss depends on the susceptibility of the soil at the time of the storm. The vulnerability of the soil to erosion can be described by intrinsic and rather static variables like slope angle, slope length, soil texture, structure and organic matter content, and is not likely to change within a season. On the other hand dynamic variables, like soil cover and the soil water content, determine the degree of susceptibility to erosion at a particular moment. Vulnerability and susceptibility are usually treated as one single soil property, like the erodibility factor in the USLE (Wischmeier & Smith, 1978), but precise estimates of the impact of a storm can only be made when the occurrence the storm is matched with the susceptibility of the soil, which can only be achieved by a process simulation model that computes soil cover and water content on a daily basis.

The RI of the April 1990 storm based on P_{24} (67.2 mm) is 4 years (Fig. 3.4). Calculation of the RI of rainfall characteristics other than R_{24} showed that the RI based on storm depth ($A=52.0$ mm) is 1 year, on kinetic energy ($E=14.0$ t ha⁻¹ cm⁻¹) is 2 years, on the highest rainfall intensity sustained for 30 minutes ($I_{30}=62.5$ mm h⁻¹) as well as for 5 ($I_5=123.0$ mm h⁻¹) and for 15 minutes ($I_{15}=92.0$ mm h⁻¹) is also 4 years (Fig. 3.5). The RI of compound characteristics like the erosivity index ($EI_{30}=87.5$ t ha⁻¹ h⁻¹) is 23 years. Other erosivity indicators (EI_{15} , AI_{15} and AI_{30}) range from 13 to 27 years, but with an average of 23 years. Most single storm-characteristics indicate a 4-year RI, while the compound-characteristics indicate an average RI of 23 years. A review of long-term rainfall data of nearby weather

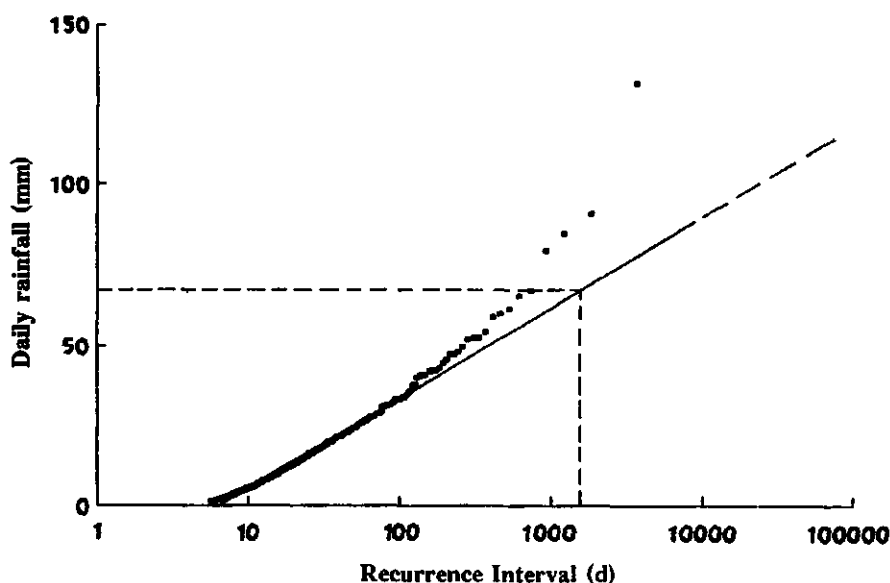


Fig. 3.4 Magnitude-frequency analysis of daily rainfall ($P_{24} \geq 1.0$ mm) at Machakos Research Station from 1983-1993: $\log(RI) = 0.036 P_{24} + 0.78$ ($n=701$, $R^2=0.979$)

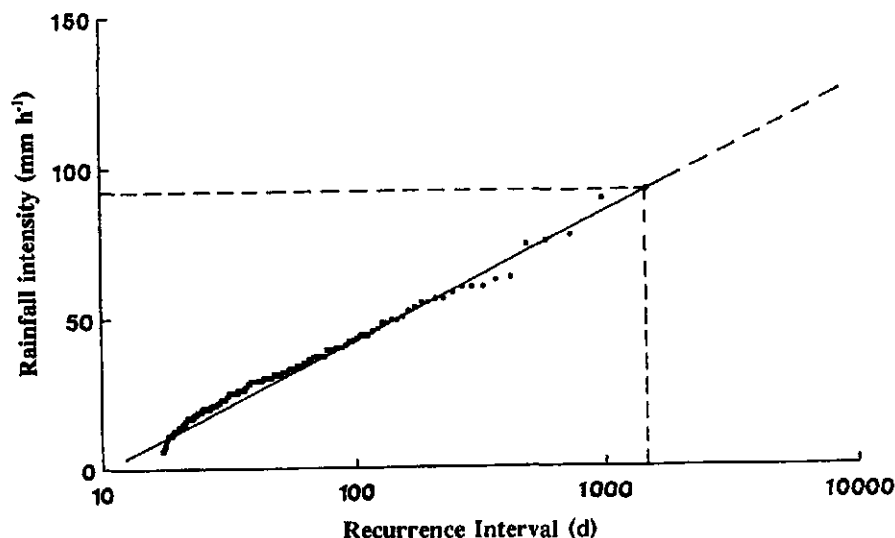


Fig. 3.5 Intensity-frequency analysis of 15-minute rainfall-intensity ($I_{15} \geq 6.0 \text{ mm h}^{-1}$) at Machakos Research Station from 1984-1992: $\log(RI) = 0.024 I_{15} + 0.95$ ($n = 171$, $R^2 = 0.989$).

stations and considering the fact that on 12 April 1985 there was even a bigger storm ($P_{24} = 131.5$, $E = 35.8$, $I_{30} = 99.5$ and $EI_{30} = 355.8$) the 4-year recurrence interval seems most likely, suggesting rainfall intensity to be a good indicator. Contour planting and good crop management may have prevented higher values of runoff and soil loss from the control plot because both measures support erosion control (Wischmeier & Smith, 1978). The annual fertilizer application and the relatively-high planting density of 3.7 for maize and 11.1 plants m^{-2} for cowpea ensured a good crop canopy cover and a quick establishment. Soils are susceptible to erosion when the cover is low and, additionally in Machakos, when the water content of the topsoil is high, because the low permeability of the subsoil can cause topsoil saturation (Kiepe, 1995). Hence, loss of topsoil will lead to a drastic reduction in infiltration rate and storage capacity, followed by more runoff and less water available for plant production. Hedgerow barriers reduced soil and water losses to a great extent, even though their performance was underestimated on five occasions. The combination of hedgerows and mulch gave the best result, a reduction in runoff to 13% and soil loss to 2%. This result is good, but from a plant production perspective not the most interesting one. A more striking feature is that the fodder hedge treatment reduced runoff to 23% and soil loss to 7%, bringing water loss only to 7 mm y^{-1} and soil loss to $1.3 \text{ t ha}^{-1} \text{ y}^{-1}$. Compared with an annual rainfall of 760 mm, a weathering rate of $5.6 \text{ t ha}^{-1} \text{ y}^{-1}$ for Machakos (Ahnert, 1982) and a nutrient enrichment ratio of 2-3 for Kenya (Gachene, 1989) the levels are acceptable and promising in the quest to attain more sustainable production systems.

Another remarkable feature is that the fodder-hedge treatment performed better than the mulch treatment, contradicting the hypothesis that protection of the soil surface by cover is better than controlling runoff with a barrier (Young, 1989). This may be explained by the fact that on a 14% slope mulch needs protection from being pushed aside. For instance, after

the major storm on 14 April 1990 rills were clearly visible on the control and on the mulch plot, but not on the hedgerow plots. It means that overland flow on the plots without hedgerows got the opportunity to concentrate into rivulets that could unimpeded run downhill, developing enough energy to transport soil. A commonly-heard explanation that biomass production of hedgerows is too low in semi-arid areas to supply enough mulch for an effective soil cover seems in this particular case unlikely. The soil cover was measured just before the storm and was 54% on the mulch plot, which should be adequate for soil protection. It seems that soil protection by mulch should be confined to gentle slopes only.

Differences in crop yields can be elucidated by regarding the nutrient balance. When runoff was not pronounced crop yield of the mulch treatment was the highest, because it was enriched by nutrients from seasonal mulch additions. However, 0.24 ha of mono-cropped tree area was needed to produce enough mulch to match the application from the hedge-with-mulch trial. So, when yields of the mulch trial are corrected for the total area exploited the cowpea yield would drop to 0.43 t ha⁻¹ and the maize yield to 2.02 t ha⁻¹. The weighted yields of the mulch plots are very similar to those of the control plot. Conversely, the fodder-hedge treatment was consistently depleted by the hedgerows because nutrients taken up for biomass production were not replaced, except for the annual fertilizer application to maize. Still, the yields were slightly higher than the control. When hedgerow biomass is fed to livestock manure can be carried back to the plot to cater, at least partly, for the lost nutrients.

3.5 Conclusion

Two cassia hedgerow systems planted as erosion barriers on a moderately-steep slope in semi-arid Kenya have shown that both systems can be considered as a suitable alternative to mechanical soil conservation. Runoff and soil loss were diminished and crop yields were not depressed by hedgerows, despite sub-optimal climatic conditions. Soil and water conservation was highest in the system where prunings were applied as surface mulch, understandably, because of the cumulative effect of erosion barrier and surface cover.

The hedgerow barrier system has most to offer when the prunings are used as fodder. Runoff and soil loss will be reduced to acceptable levels, crop yields maintained or increased and hedgerow prunings can be utilised and provide additional income from livestock production. Future research should include a thorough economic analysis of the fodder hedgerow barrier system that will take the complete production system into account, including livestock production, labour requirements and an assessment of the long-term effect of soil conservation on the productivity.

Crop yields were the highest in the mulch treatment, which was not surprising because the system received extra nutrients from mulch produced outside the plot and it did not suffer from potential resource competition by the hedge. However, after correction for the area occupied to produce the mulch the yield advantage disappeared. The effect of mulch on runoff was less than the impact of hedgerows on runoff.

4 Effect of *Cassia siamea* hedgerow barriers on soil physical properties.

Abstract

Hedgerows of *Cassia siamea* were planted 4 m apart in a maize/cowpea rotation on a 14% slope of a Lixisol/Alfisol in 1988 at Machakos, Kenya. Infiltration rates were measured in situ across hedgerow barriers with a drip infiltrometer. During the dry season the steady infiltration rate under the hedgerows was 135 mm h⁻¹ while on the alleys in between it was 41-49 mm h⁻¹ and on the control plot 39-48 mm h⁻¹. Corresponding values for the wet season were 69 mm h⁻¹ for the hedge and 8-11 mm h⁻¹ for the alley. Removal of the hedge plants revealed that much of the increase is due to significantly more macropores in the topsoil beneath the hedgerow than in the topsoil beneath the alley. Differences in pore size distribution in the subsoil were small and not significant. Total increase in average infiltration rate of the hedgerow barrier system in the dry season is 30% and in the wet season is 94% as compared to the alley. The combined effect of above and below-ground changes makes hedgerow barriers valuable for runoff control.

4.1 Introduction

Hedgerow barriers are rows of periodically pruned trees or shrubs grown in between crops and planted close together on the contour for soil conservation. From a comparison of the rate of terrace formation and crop yields between four different methods of controlling soil erosion in a semi-arid environment, hedgerow barriers came out as the most promising one (Kiepe & Young, 1992). Hedgerow barriers are semi-permeable and until recently it was believed that they could control runoff during low to medium intensity rain showers, but that hedgerows would not be effective during heavy storms. However, the impact of hedgerows on runoff increases when storms get heavier (Kiepe & Rao, 1994). To explain this effect of hedgerow barriers the processes involved should be disentangled and quantified.

Agroforestry systems are biologically complex systems that need to be divided into spatially homogenous zones to facilitate analysis. The most simple subdivision of a hedgerow barrier system is into a zone with crops (the alley) and a zone with trees (the hedgerow). The hedgerow barrier controls erosion in two ways. First as a semi-permeable physical obstruction to runoff, causing runoff to infiltrate upslope from the hedge and during flow through the hedge, where it subsequently spreads over the next alley downhill. Second, as a biological obstruction for runoff. Infiltration under the hedge is improved by better physical conditions of the topsoil due to the activity of roots. A frequent pruning regime of trees results in an increase in the number of roots. When trees are pruned at low level (0.25 m from the soil surface) more and finer roots are formed in the topsoil than from unpruned trees or trees pruned at greater heights above the soil (0.50 and 0.75 m) (Van Noordwijk et al, 1991a). Part of the below-ground biomass of the tree dies immediately after pruning. Dead roots and subsequent decay promote the formation of organic matter, which in turn has

a positive effect on the infiltration rate (Wischmeier and Mannering, 1965). Remnants of decaying roots themselves behave as macropores which can function as channels for bypass flow and facilitate percolation (Van Noordwijk et al., 1991b). Moreover, soil fauna appears to be more abundant under hedgerows, due to litterfall, application of prunings and a suitable microclimate (Brussaard et al., 1993). The soil fauna is also attracted by decomposing roots as a food source and their pathways, and the pathways of their predators, can act as preferential flow paths too (Bouma et al., 1982). Organic matter, old root channels and soil fauna all have a positive influence on the permeability of the soil under hedgerows.

Previous work (e.g. Coster, 1938) has revealed that hedgerow barriers can reduce runoff and, consequently, increase infiltration. From double-ring infiltrometer measurements it is known that the cumulative infiltration beneath the hedge is higher than in the adjacent alley (Lal, 1989). However, the extent of the anticipated area of higher infiltration and the magnitude of the infiltration increase are currently unknown. The objective of this study was to quantify the changes in infiltration rate beneath the hedgerow barrier and to determine the extent of the area in question as a basis for designing more efficient conservation systems.

4.2 Materials and methods

4.2.1 Experimental site

Four large runoff plots of 400 m² were installed on a 14% slope at the ICRAF Research Station (1° 33' S, 37° 14' E) at 1600 m altitude in Machakos, Kenya. Average annual rainfall is 760 mm, distributed over two seasons of 365 mm and 330 mm each. The soil is a sandy clay loam over sandy clay; 150 cm deep, overlying the gneissic Precambrian basement complex. The soil is classified as Chromic Luvisol (Kibe et al., 1981), and updated as Haplic Lixisol (FAO, 1988) or Kanhaplic Rhodustalf (Soil Survey Staff, 1990). Maize and cowpea were grown in sequence in all treatments. Hedgerows of *Cassia siamea* Lam. (Leguminosae, Caesalpinioideae), a non-nodulating leguminous tree, were planted on the contour in two runoff plots in 1988. The hedgerows were pruned each season to a height of 0.3 m. The trees were planted 0.25 m apart within the row and at 4 m distance between two neighbouring hedgerows. The third plot was mulched and the fourth plot was the control where there was no additional conservation measure. At the bottom of each plot equipment for runoff and sediment collection was operational from the beginning of 1990.

4.2.2 Choice of the drip infiltrometer

Infiltration was measured with the aid of a modified commercially-available small drip infiltrometer, easy to transport, using little water and has supporting legs that are of adjustable height (Kamphorst, 1987). This infiltrometer was selected because it fulfilled four requirements specific to this study. First, the infiltrometer permits excess water to run downhill without generating a hydraulic head, that could lead to deceptively high infiltration values. Second, it leaves surface crusts intact, which is important for the soils of Machakos that are reported to have a tendency to form surface crusts (Barber et al., 1979, Kibe et al., 1981). Third, the infiltrometer had to be small because it would be used to determine the

extent of the relatively small area of higher infiltration. The fourth requirement was that the instrument could be placed over a pruned hedgerow, without the need to cut it down.

4.2.3 Soil infiltration - theoretical framework

The infiltration rate was calculated by subtracting runoff from rainfall. Theoretically, the infiltration rate is infinite at time zero and decreases asymptotically to its final infiltration rate as time increases. The final infiltration rate is the 'saturated hydraulic conductivity under ideal conditions'. When unconfined infiltrometers are used under field conditions the status of saturated hydraulic conductivity is hardly ever reached, but the effective steady infiltration rate appears to be constant after a certain period (Stroosnijder, 1976). The effective infiltration rate is influenced by conductivity and sorptivity. In a wet soil the conductivity will be higher, but in a dry soil the sorptivity will be higher. Due to the overriding importance of the three-dimensional expansion of the wetting front in a dry soil, the combined effect will be that the infiltration rate is higher in a dry soil than in a wet soil.

4.2.4 Experimental measurements

Infiltration measurements were made along 4 m long transects in the hedgerow plots and in the control plot. Four transects were laid out across randomly-selected hedgerows, with the restrictions that the transects were running perpendicular to the hedgerows and that each transect started in the middle of an alley. Measurements were made every 0.5 m, at 9 locations of 0.25 x 0.25 m per transect. For each transect, two measurements were made in the hedgerow on the same location. First, one measurement was made with the stem of the tree still present in the middle of the location. Then, the tree was cut exactly at ground level so that the soil surface was left untouched and the above-ground part of the tree was carefully removed. Next, the measurement was repeated so that the increase in infiltration rate caused by the roots only could be separated from the increased infiltration rate due to the combined effect of roots and tree stem. Additionally, six measurements were made on randomly-selected locations on the control plot.

Infiltration runs were carried out in two transects at the end of the dry season in 1991 and one transect in 1992, on uncultivated land immediately after the harvest of the crop. After observing a dramatic increase in runoff from the control plot in the rainy season, while the increase in runoff from the hedgerow plots was little, it was decided to measure the infiltration rates of the fourth transect in the rainy season. This way it could be checked if the increased infiltration under the hedgerow could sustain a relatively higher intake rate when the soil was wet.

Saturated hydraulic conductivity, bulk density and water release characteristics were measured in the laboratory from undisturbed soil samples. Samples were taken from an adjacent hedgerow barrier research trial which was initiated one year later in 1989, also on a 14% slope and the same soil. Soil cores were taken with standard pF-rings of 53 mm diameter from three physically-different horizons; 1) in the topsoil around 15 cm deep, 2) the upper subsoil around 80 cm deep and 3) in the lower subsoil around 140 cm deep,

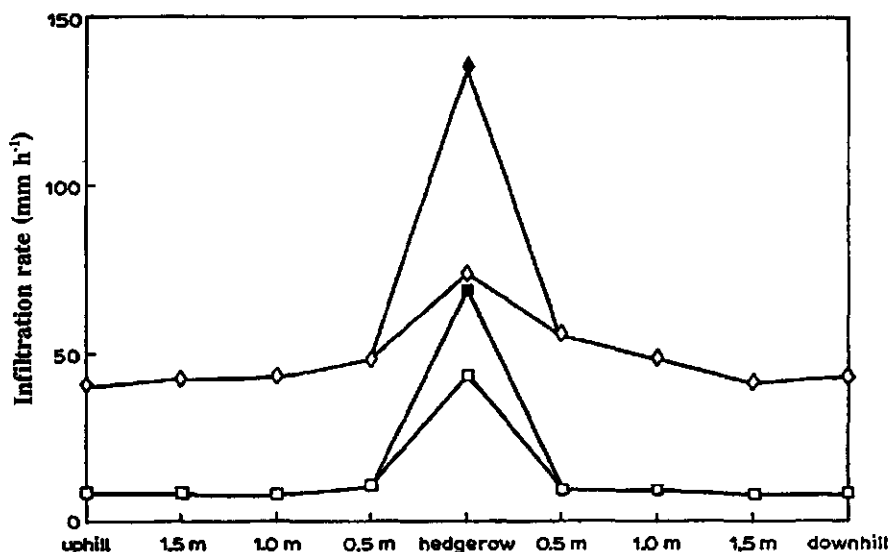


Fig. 4.1 Effective steady infiltration rates measured in transects across hedgerow barriers; in wet soil with a complete hedgerow present (■), in wet soil after removal of the stem (□), in dry soil with a complete hedgerow present (◆) and in dry soil after removal of the stem (◇).

replicated three times. The samples were taken randomly in the hedge and at 1.0 m and 2.0 m distance from the hedge.

4.3 Results

In the dry season, infiltration rates measured in the alley were 41-49 mm h⁻¹ and were no different from the control plot (average infiltration 44 mm h⁻¹). The infiltration rate beneath the hedge was 135 mm h⁻¹, which was significantly different ($P < 0.001$) from the alley values. Subsequent separation of the above and below-ground effect of the hedgerow resulted in an infiltration rate of 74 mm h⁻¹ (significantly different at $P < 0.01$). The results from measurements of the fourth transect on a wet soil are quite different in absolute terms, but not in relative terms. The infiltration data show that the rate on the zone previously under crops dropped from 41-49 mm h⁻¹ to 8-11 mm h⁻¹. Despite the drop in infiltration rate on a wet alley, the infiltration rate under the hedge still showed an increase to 69 mm h⁻¹, while the hedgerow area without stem still accepted 44 mm h⁻¹.

The average infiltration rate in the dry season of the alleys excluding the hedgerows was 44 mm h⁻¹, while the average infiltration rate including the hedgerows was 57 mm h⁻¹. Without the physical obstruction of the tree stem present the average value of the transect was 50 mm h⁻¹ (Fig. 4.1). This means that, through the presence of the hedgerow, the infiltration rate of the transect increased 30% and without the stem increased 14%. In the rainy season, the

Table 4.1 Laboratory measurements of saturated hydraulic conductivity (K_{sat}) in $mm\ h^{-1}$ and bulk density (d_B) in $g\ cm^{-3}$ (average of three measurements) from soil cores taken at three depths

	K_{sat}	d_B	K_{sat}	d_B	K_{sat}	d_B
Location	(0.0-0.3 m)		(0.3-1.1 m)		(1.1-1.5 m)	
Crop control	35.1	1.38	8.2	1.51	8.4	1.69
2.0 m uphill	33.8	1.41	2.8	1.59	2.5	1.63
1.0 m uphill	34.9	1.39	1.2	1.53	3.5	1.64
Hedgerow	60.8	1.31	3.2	1.56	8.7	1.62
1.0 m downhill	43.7	1.39	1.2	1.53	0.0	1.66

average steady infiltration rate of the alley excluding the hedgerow was $8.6\ mm\ h^{-1}$, while the infiltration rate of the transect including the hedgerow with stem was $16.7\ mm\ h^{-1}$ and without the stem was $13.5\ mm\ h^{-1}$. This means that the hedgerow system can accept 94% more water on a wet soil than the system without hedgerows, of which 57% is due to below-ground effects.

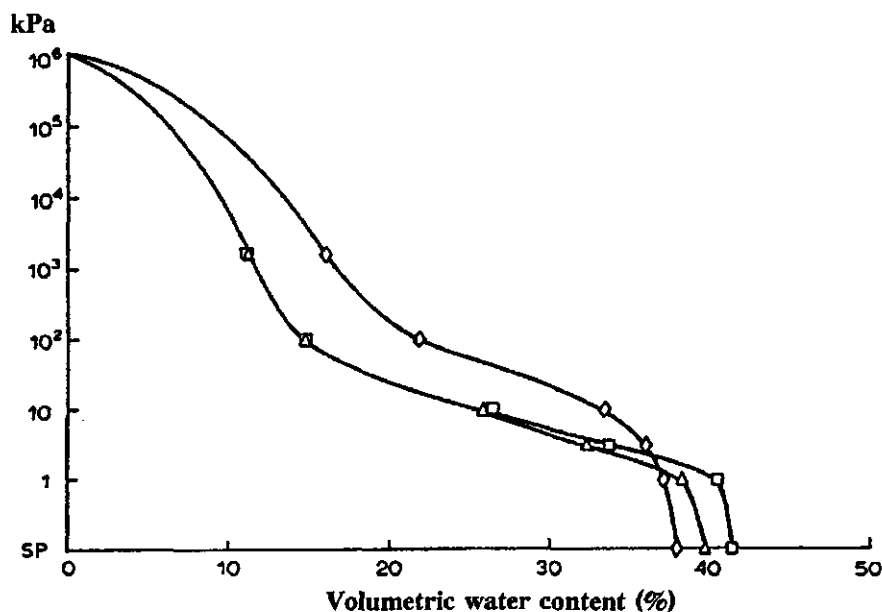


Fig. 4.2 Soil water characteristics of the topsoil (0-30 cm) beneath the hedgerow (□) and beneath the alley (Δ). The topsoil beneath the hedgerow holds significantly more water when saturated (SP), at 1 kPa ($P < 0.05$) and 3 kPa ($P < 0.1$). No significant difference was found in the subsoil (30-150 cm) (◇).

Saturated hydraulic conductivity values of the topsoil (Table 4.1) can be compared with the infiltration rates of a wet soil without the presence of the tree stem. The saturated conductivity of the middle alley (2.0 m uphill) was 33.8 mm h⁻¹, which was close to the average crop control rate of 35.1 mm h⁻¹, while the average value under the hedge was 60.8 mm h⁻¹. The conductivity rates of the subsoil were much lower and showed little difference between hedgerow and alley. The differences in water-release characteristics between the hedgerow and the alley in the topsoil were confined to the topsoil. The topsoil beneath the hedgerow held significantly more water at low suction than beneath the alley (Fig. 4.2) and the bulk density of the topsoil beneath the hedgerow was significantly lower ($P < 0.05$) than the alley (Table 4.1).

4.4 Discussion

Macropores are more abundant in the topsoil beneath hedgerows than beneath the alley. The extra pore space beneath the hedgerow is of crucial importance for capturing part of the overland flow. In the dry season, as well as the rainy season, the steady infiltration rate under the hedge was 3-8 times the infiltration rate in the alley. After removal of the stem the infiltration rate underneath the hedgerow dropped, but was still 2-5 times the rate in the alley. Therefore, the increase in infiltration rate is thought to be due to a combination of two mechanisms. First, the tree stem acts as a physical barrier, and secondly, the tree roots improve the soil structure. The infiltration rate of the alley remained unchanged compared with the crop control. Infiltration rate increased only directly beneath the hedgerow.

Hydraulic conductivity, bulk density and water-retention values confirm that hedgerows increase the porosity of the topsoil. The drop in hydraulic conductivity from the topsoil to the subsoil and the low values of the infiltration rates on a wet soil indicate that topsoil saturation can be a problem of these soils. Simultaneously, the drop in infiltration on a wet soil as compared with the infiltration on a dry soil can be explained by topsoil saturation and not by the formation of a surface crust. As indicated above, the difference between the infiltration in the alley and underneath the hedge is relatively more pronounced in the wet season than in the dry season (Fig. 4.1). Hence, the importance of the below-ground effect on the infiltration rate becomes greater in wet soil than in dry soil. Neutron probe measurements showed that after a rain storm the soil water content of the subsoil is significantly higher and that the wetting front descends faster beneath the hedgerow than beneath the alley (Kiepe, unpublished data). Apparently, water is drained either along tree roots or in old root channels, which are usually found in clusters in compact subsoils. The porosity of the subsoil matrix is not changed and increased drainage is, therefore, not reflected in the water retention curves or hydraulic conductivity values of the matrix. Presumably, the sampling procedure that was used for the conductivity measurements is inappropriate to detect the preferential flow paths. Infiltration of dye may be used to trace preferential flow paths, but conductivity measurements on large and undisturbed soil samples, containing active and dead roots, are needed to quantify the preferential flow. The presence of preferential flow will explain the feature that hedgerow barriers are increasingly effective as the soils get wetter.

4.5 Conclusion

Experimental studies demonstrate that hedgerows increase infiltration of the topsoil. The infiltration process under the hedgerow is governed by two factors. One is the barrier-effect caused by physical obstruction of the tree stem to overland flow and the second factor is a better soil structure due an increase in macropores in the topsoil beneath the hedgerow. The zone of increased infiltration is restricted to the area underneath the hedgerow.

Mechanical soil conservation measures, like banks and ditches, increase infiltration by water retention. In separating the barrier effect and the improved soil-structure effect of the hedgerow on infiltration, the relative importance of both the mechanical effect and the biological conservation effect of the hedgerows is elucidated. Separating the two effects clearly shows the auxiliary effects of trees on infiltration as compared with mechanical soil conservation measures.

The increased infiltration rate under hedgerows is sustained when the soil is wet, which makes hedgerow barriers effective during heavy downpours. This is contrary to the widely-accepted view that semi-permeable barriers will give way during heavy storms and solid banks will not. However, it is the below-ground changes together with the barrier-effect that make the hedgerows a powerful tool in reducing runoff and combating soil erosion.

5 Soil water status beneath *Cassia siamea* hedgerow barrier systems after rain storms

Abstract

On a 14% slope of a Lixisol/Alfisol in Machakos, Kenya, trees were planted dispersed (1 x 1 m) and in 4 and 8 m wide rows as hedgerow barriers to examine their influence on infiltration and redistribution of soil water for erosion control and plant production. Soil-water content-measurements were taken with a neutron probe every week during four growing seasons and on four occasions after a rain storm. There was no difference detected in water content fluctuation between the soil under crops and under dispersed trees, but the soil beneath the hedgerow barriers accumulated more water after each rainstorm than the adjacent alley where crops were grown. The contrast in water content between hedgerow and alley disappeared at the end of the cropping season. The spatially-weighted amount of water stored in the hedgerow barrier systems was higher than in the control, which was also indicated by the higher total above-ground dry matter production in the hedgerow treatments (13.4-14.4 t ha⁻¹ y⁻¹) compared to the crop control (11.0 t ha⁻¹ y⁻¹). In the treatment where hedgerows were planted 8 m apart, maize grain yield was higher (5.3 t ha⁻¹ y⁻¹) than in the crop control (4.7 t ha⁻¹ y⁻¹).

5.1 Introduction

Hedgerow barriers are rows of periodically pruned trees or shrubs grown in between crops and planted close together on the contour for soil conservation. Hedgerows have been used for soil conservation since the beginning of this century, albeit on a modest scale (Kiepe & Rao, 1994). Despite favourable reports from the humid tropics about their ability to control erosion (Young, 1989) no attempt was made to study this technology in detail. From a comparison of four different ways of controlling soil erosion in a semi-arid environment, the hedgerow barrier technology has shown the greatest promise (Kiepe & Young, 1992). This finding resulted in the implementation of a set of experiments, designed to quantify the capability of hedgerow barriers to control soil erosion by water and explain the processes involved. Hedgerow barriers promote infiltration (Kiepe, 1995) but the subsequent post-infiltration redistribution of water determines where the water will be stored. Plant production under rainfed conditions in semi-arid areas starts in the rainy season, but usually continues well into the dry season. During the latter period water uptake depends almost entirely on the availability of water in the rooting zone. It is important to locate and quantify the reservoirs where water will be stored and from which it can be utilized (Stroosnijder, 1976).

5.2. Materials and methods

5.2.1 The experimental area

The trial was established a 14% slope of the ICRAF Research Station in Machakos, Kenya (1° 33' S, 37° 14' E) at an altitude of 1600 m. The soil of the experimental trial is 1.5 m deep, a sandy clay loam over a sandy clay (Table 5.1), and is classified as Chromic Luvisol (Kibe et al., 1981) and revised by the author as Haplic Lixisol (FAO, 1988) or Kanhaplic Rhodustalf (Soil Survey Staff, 1990). The area is semi-arid and the rainfall distribution is bimodal. The average rainfall (10 year mean) of the long rains (LR) is 330 mm (± 155 mm), while that of the short rains (SR) is 365 mm (± 125 mm). Another 65 mm (± 50 mm) falls in scattered showers off-season. There is a large variability in annual and seasonal rainfall and also in rainfall reliability (Braun, 1977).

The actual rainfall, 352 mm, 222 mm, 808 mm, and 84 mm, respectively, of the four seasons (SR 1991; LR and SR of 1992; LR of 1993) was used to characterize soil water measurements: the first rainy season was about average, the second below, the third well above, and the fourth season well below average. Spatial arrangement of soil-water content-values remained the same for each season and each treatment despite the quantity of rainfall, although the extent of changes in soil water content differed between seasons as well as between treatments.

5.2.2 Design of the experimental plots

Soil-water content-measurements were made during four growing seasons, from September 1991 until August 1993. Ten runoff plots, five treatments with two replicates, of 5 x 32 m were installed on a 14% slope of the ICRAF Research Station in Machakos in 1989. The top and both sides of each plot were confined by a 0.3 m high metal strip to avoid cross flow. Runoff was intercepted at the bottom of each plot by wash traps and subsequently channelled through drain pipes into collection tanks. Four treatments were planted with cassia trees (*Cassia siamea*, Lam., syn. *Senna siamea*), a non-nodulating legume, and one treatment served as a crop control (CC). In three of the cassia treatments these trees were planted on the contour as hedgerows and in the fourth treatment trees were planted dispersed, 1 x 1 m in echelon, as a tree control (TC). The hedgerows as well as the dispersed trees were pruned twice a year to a height of 0.3 m, immediately before the onset of the rains. The prunings were applied as mulch. The replication of the four treatments with trees is random. The CC-treatments are located 50 m away from the cassia treatments to avoid unwanted below-ground interaction. The spread of cassia roots can cause below-ground interference of more than 15 m (Hauser, 1993).

Three different treatments can be distinguished with respect to alley width and hedgerow density (Fig. 5.1). The three hedgerow treatments were: single-row hedges with a 4 m alley in between (S4), double-row hedges with a 4 m alley in between (D4) and with an 8 m alley in between (D8). Trees in a single row were planted 0.25 m apart and a double row consists of two offset single-rows, with 0.25 m distance in between. Crops planted between the hedgerows and in the crop control were maize (*Zea mays* cv. Katumani composite B) and

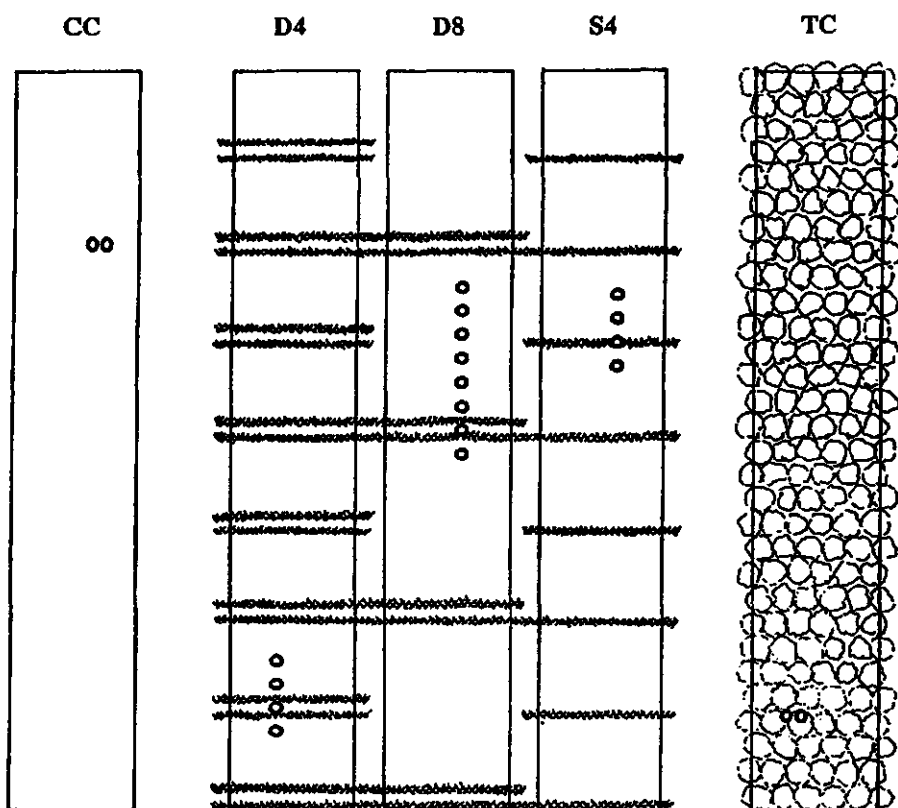


Fig. 5.1 Layout of treatments and transects of neutron-probe access-tubes (o) in the crop-control (CC), tree-control (TC) and the three *Cassia siamea* hedgerows treatments: single-row hedges planted 4 m apart (S4), and double-row hedges planted 4 m apart (D4) and 8 m apart (D8).

cowpea (*Vigna unguiculata* cv. K 80) in rotation. During two seasons (SR 1991 and LR 1992) maize was planted in succession and received 200 kg N and 60 kg P fertilizer to eliminate nutrient competition. Cowpea was planted in the short rains of 1992, but suffered from root and collar rot, which seriously affected the yield. Maize was planted in the long rains of 1993, but with only 84 mm of rain a crop failure was inevitable. Hence, only plant production data of SR 1991 and LR 1992 are reported.

5.2.3 Experimental design of the soil water measurements

Fifteen series of aluminium neutron-probe access-tubes were installed perpendicular to the hedgerows to a depth of 1.5 m into the soil. The tubes were positioned so that one tube stood exactly in the middle of a single-tree hedge or, in case of 2-row hedges, between the rows, while the others were placed 1.0 m apart in a transect at right angles to the hedge (Fig. 5.1).

Table 5.1 *Laboratory measurements of the volumetric soil water content (θ in %) when saturated (ST at 0 kPa), at field capacity (FC at -10 kPa) and at permanent wilting point (WP at -1.5 MPa), total storage of water (mm) in the top 1.5 m of the soil profile, soil texture (%), data from Kibe et al. 1981) in sand (S, > 50 μm), silt (Z, 2-50 μm) and Clay (C, < 2 μm) and bulk density (d_b in g cm^{-3}), average of 6 replicates sampled at every 0.2 m depth with standard deviation in parentheses).*

Depth (m)	Soil water			Soil texture			Bulk density d_b
	ST	FC	WP	S	Z	C	
0.0-0.3	40	26	11	62	8	30	1.35 (0.10)
0.3-1.1	38	34	16	49	6	45	1.44 (0.12)
1.1-1.5	37	32	16	38	3	59	1.63 (0.08)
Storage	572	478	225				

This resulted in series of four tubes in the 4 m hedgerow treatments and series of eight tubes in the 8 m hedgerow treatment. In the tree-control and crop-control treatments tubes were inserted as pairs, one tube next to a plant and one in the middle of two neighbouring plants. The entire layout of five series (20 access tubes) was randomly replicated three times over the experiment. The experimental plots were replicated twice, which meant that some plots had one series of access tubes, while other plots had two series.

Soil water content measurements were taken once a week using a neutron probe (Ditcot Soil Moisture Probe Type I.H. III). On four occasions additional measurements were made immediately after a storm. The neutron probe was calibrated by comparison of the count-ratios with gravimetric water content measurements, obtained from conventional oven-dry weights and multiplied by bulk density data (Gardner et al., 1991). Calibration of the neutron probe was done separately for all three physically-different soil horizons (Table 5.1).

5.3. Results

The volume of data collected over the four seasons forced a selection of the most representative rainfall events. From the hedgerow treatments, the treatment with the double-row hedge and an 8 m alley (D8) was selected because it depicts the various processes most clearly, magnifying the contrast between the soil of the alley and the soil beneath the hedgerow. In the short rains of 1991, rainfall was about average (352 mm) and so examples were selected from one season, from October 1991 until March 1992.

5.3.1 Temporal fluctuation of soil water under crop and hedgerows

Fluctuations in water storage in the top 1.5 m of the soil profile were usually simultaneous for all treatments. Except after heavy rain storms the total water storage beneath the hedgerows was significantly greater ($P < 0.001$ on Julian day 290 and 322, and $P < 0.05$ on Julian day 354 in SR 1991) than under the crop (Fig. 5.2). There were no differences

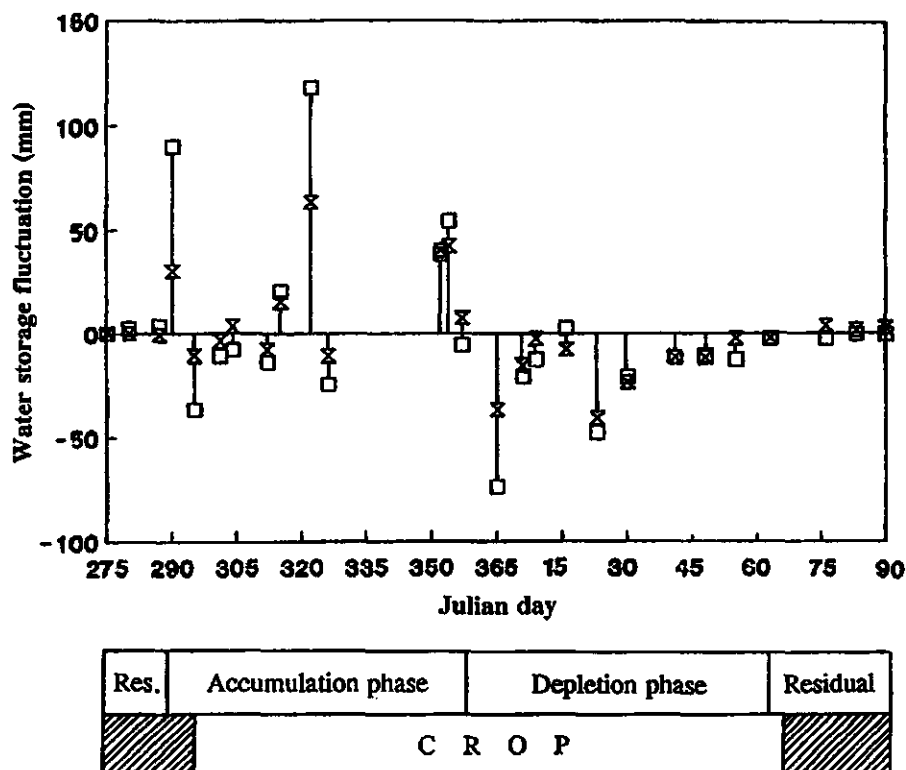


Fig. 5.2 Fluctuation in total water (mm) stored in the top 1.5 m of soil under the crop (X, mean of control and the middle-alley), and beneath the *Cassia siamea* hedgerow (\square) from 2 October 1991 (Julian day 275) until 30 March 1992 (Julian day 90).

between this increase in the control plot and in the alley. In the days following these storms part of the additional soil water beneath the hedgerows was depleted faster than under the crop (Julian day 295, 326 and 365). Increases of additional water stored beneath hedgerows were observed on 3, 2, 5 and 2 occasions in the first, second, third and fourth season respectively.

Temporal fluctuations in the storage of water can be characterized by three phases (Fig. 5.3). First, the accumulation phase, which is a period when storage of water increases. It starts at the onset of the rains and lasts as long as the input is higher than the output. The next phase is the depletion phase. This phase starts when the total water stored decreases and lasts until it gets constant. This moment ideally coincides with senescence of the standing crop. Third is the residual phase, which is a period when few fluctuations occur. During this phase input and output are small and do not seriously influence the total soil-water storage. Seasonal changes of the total soil-water storage showed that the soil beneath the hedgerows held more water than the soil under the alley for 130 days, from Julian Day 290 to Julian day 55 (Fig. 5.3). This period encompasses the entire growing season of the crop.

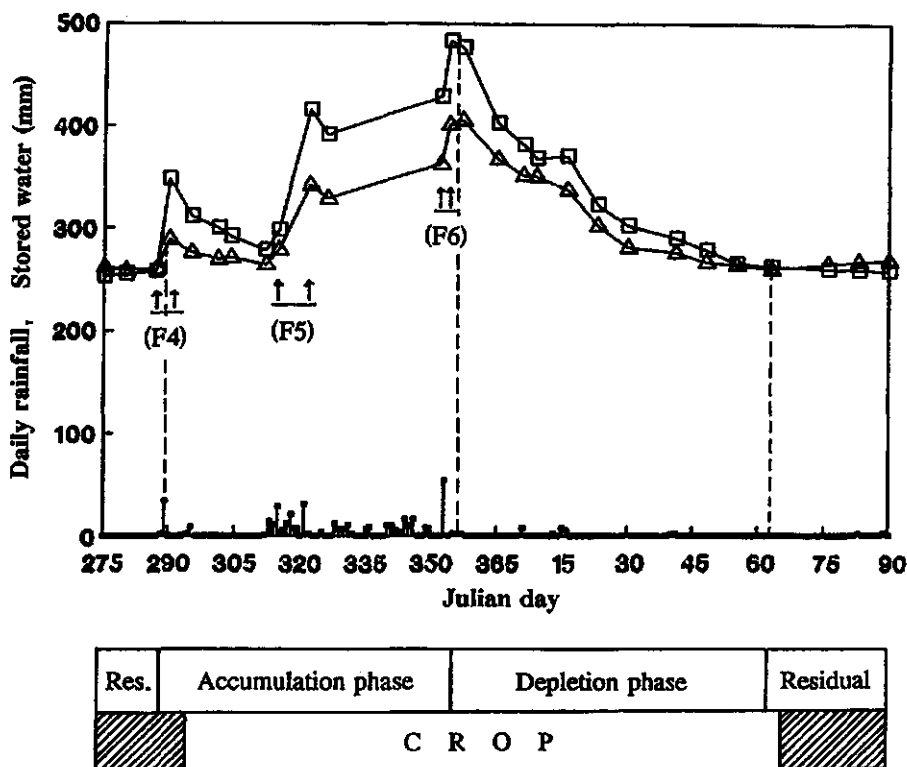


Fig. 5.3 Daily rainfall (vertical bars) and subsequent changes in the storage of water in the top 1.5 m of soil in treatment D8 beneath the *Cassia siamea* hedgerow barrier (□) and under the middle of the alley (Δ) from 2 October 1991 (Julian day 275) until 30 March 1992 (Julian day 90). The total seasonal rainfall was 352 mm. Arrows indicate dates related to Fig. 5.4 (F4), Fig. 5.5 (F5) and Fig. 5.6 (F6).

5.3.2 Spatial distribution of soil water under crop and hedgerows

In the tree and crop control treatments no distinct lateral distribution patterns were found. Conversely, in the three hedgerow treatments distinct patterns were found. Before the onset of the rainy season water was laterally equally distributed (Fig. 5.4a)¹. The day after the first rain storm (Fig. 5.2, Julian day 289) the wetting front reached a depth of 0.2-0.4 m beneath the alley and 0.6 m beneath the hedgerow. The increase in soil water content as well as the total water storage was significantly higher beneath the hedgerow than beneath the

¹Paired detailed measurements are used to link temporal to spatial distribution of soil water. Pairs are indicated in Fig. 5.3 with reference to Fig. 5.4-5.6., where a. refers to the situation before a rainfall event and b. to the aftermath.

alley (Fig. 5.4b). This pattern of redistribution of soil water under hedgerows was representative of the aftermath of every storm. The second rainfall event happened on Julian day 321. Before the storm there was no difference horizontally in water content in the subsoil (Fig. 5.5a). After the storm the wetting front beneath the alley reached down to 0.65 m while that beneath the hedgerow was at 1.10 m (Fig. 5.5b). The third event happened on Julian day 354. Due to preceding rainfall the soil water content beneath the hedgerow was higher than in the alley (Fig. 5.6a), but this difference in water content increased even more (Fig. 5.6b). At this time, the area where the soil water content was high expanded laterally to 1 m either side of the hedgerow.

5.3.3 Biomass production of crops, trees and hedgerows

Maize grain yield of treatment D8 was higher than the yield of the crop control for both seasons reported (Table 5.2). Grain yields of treatment S4 and D4 were not different from the crop control. The total above-ground dry-matter production, which is sum of maize grain (MGY), maize stover (not presented) and hedgerow prunings (HPR), of all hedgerow plots was higher than the production of the crop control. The maize was harvested row-by-row and there were no differences found in yield between the rows. The increase in dry matter production of treatment S4 and D4 must, therefore, be due to a higher transpiration rate from the hedgerow area.

5.4 Discussion

Temporal fluctuations in soil water content as well as the spatial pattern of soil water content under crops, dispersed trees and hedgerows were consistent for each treatment for all four seasons. The initially dry soil at the start of a growing season was recharged by rainfall and overland flow and subsequently soil water accumulated steadily. Accumulation of soil water

Table 5.2 Dry matter production ($t\ ha^{-1}$) under rainfed conditions. Maize grain yield (MGY), *Cassia siamea* hedgerow prunings (HPR) and total above-ground dry matter production (TDM) of the short rains of 1991 and long rains of 1992 in the crop-control (CC), single-row hedges planted 4 m apart (S4), double-row hedges planted 4 m apart (D4) and 8 m apart (D8) and the tree-control (TC)

	SR 1991			LR 1992			Annual total		
	MGY	HPR	TDM	MGY	HPR	TDM	MGY	HPR	TDM
CC	2.55	-	6.26	2.13	-	4.75	4.68	-	11.01
S4	2.63	1.05	8.28***	1.96	0.76	5.09	4.59	1.81	13.37***
D4	2.59	1.49	8.00***	1.97	1.05	5.53*	4.56	2.55	13.53***
D8	2.92***	0.65	8.68***	2.37*	0.52	5.75**	5.29**	1.17	14.43***
TC	-	4.13	4.13	-	2.99	2.99	-	7.12	7.12

Fig. 5.4a *Spatial redistribution of soil water under an 8 m wide Cassia siamea hedgerow barrier system. Volumetric soil water content (%) and the total storage of water (mm) in the top 1.5 m of soil are presented in a cross section through the hedgerow on 14-10-1991 (Julian day 287).*

Depth (m)	4m uphill	3m uphill	2m uphill	1m uphill	Hedge	1m down	2m down	3m down
0.2	5	6	5	5	7	7	6	5
0.4	13	15	14	13	12	14	15	15
0.6	18	18	17	19	18	17	18	18
0.9	21	21	21	21	21	20	20	21
1.2	21	21	20	21	20	21	20	21
1.5	21	21	20	21	20	20	21	21
Storage	260	267	256	262	258	257	265	264

Fig. 5.4b *Spatial redistribution of soil water under an 8 m wide Cassia siamea hedgerow barrier system. Volumetric soil water content (%) and the total storage of water (mm) in the top 1.5 m of soil are presented in a cross section through the hedgerow on 17-10-1991 (Julian day 290).*

Depth (m)	4m uphill	3m uphill	2m uphill	1m uphill	Hedge	1m down	2m down	3m down
0.2	18	21	19	18	26**	23	19	21
0.4	16	20	18	19	26**	26**	20	18
0.6	18	18	17	18	26***	18	18	18
0.9	20	21	20	21	21	19	20	20
1.2	21	21	20	20	22*	21	20	21
1.5	20	20	20	20	20	19	21	21
Storage	289	303	289	294	348***	312*	297	299

0-8

9-16

17-24

25-32

33-40

Volumetric soil water content (%)

Fig. 5.5a Spatial redistribution of soil water under an 8 m wide *Cassia siamea* hedgerow barrier system. Volumetric soil water content (%) and the total storage of water (mm) in the top 1.5 m of soil are presented in a cross section through the hedgerow on 11-11-1991 (Julian day 315).

Depth (m)	4m uphill	3m uphill	2m uphill	1m uphill	Hedge	1m down	2m down	3m down
0.2	15	14	15	13	19*	19	14	15
0.4	16	18	18	17	17	20	18	18
0.6	18	18	18	20	17	18	18	18
0.9	20	21	20	20	22	19	20	21
1.2	21	21	21	20	21	21	20	21
1.5	20	21	20	20	21	19	22	21
Storage	279	289	285	283	298	292	284	289

Fig. 5.5b Spatial redistribution of soil water under an 8 m wide *Cassia siamea* hedgerow barrier system. Volumetric soil water content (%) and the total storage of water (mm) in the top 1.5 m of soil are presented in a cross section through the hedgerow on 18-11-1991 (Julian day 322).

Depth (m)	4m uphill	3m uphill	2m uphill	1m uphill	Hedge	1m down	2m down	3m down
0.2	20	20	21	20	30**	25	24	21
0.4	26	30	28	28	29	28	27	25
0.6	29	31	27	29	32	28	29	28
0.9	23	24	21	23	32***	21	23	23
1.2	21	21	21	20	25***	22	20	21
1.5	20	21	20	21	22	20	22	21
Storage	342	359	337	347	416***	350	355	343

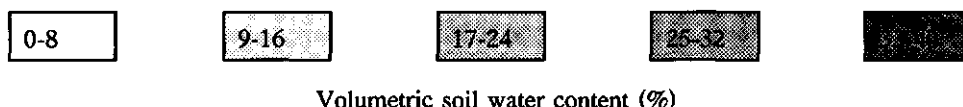


Fig. 5.6a *Spatial redistribution of soil water under an 8 m wide Cassia siamea hedgerow barrier system. Volumetric soil water content (%) and the total storage of water (mm) in the top 1.5 m of soil are presented in a cross section through the hedgerow on 18-12-1991 (Julian day 352).*

Depth (m)	4m uphill	3m uphill	2m uphill	1m uphill	Hedge	1m down	2m down	3m down
0.2	13	10	11	13	21***	18*	13	14
0.4	25	26	25	25	26	27	27	27
0.6	29	29	28	31	28	27	30	29
0.9	29	30	29	32	30	32	30	29
1.2	26	29	25	30	32*	31	23	26
1.5	21	22	21	26***	31***	24*	22	22
Storage	363	374	351	399*	429**	403*	365	367

Fig. 5.6b *Spatial redistribution of soil water under an 8 m wide Cassia siamea hedgerow barrier system. Volumetric soil water content (%) and the total storage of water (mm) in the top 1.5 m of soil are presented in a cross section through the hedgerow on 20-12-1991 (Julian day 354).*

Depth (m)	4m uphill	3m uphill	2m uphill	1m uphill	Hedge	1m down	2m down	3m down
0.2	20	15	16	18	29**	25	20	21
0.4	30	31	31	30	31	32	31	31
0.6	31	31	31	31	31	31	31	32
0.9	31	32	31	31	31	32	31	32
1.2	28	30	26	31	31	32*	26	27
1.5	21	22	21	26***	31***	25***	22	21
Storage	402	410	388	438*	483***	444*	409	408

0-8

9-16

17-24

25-32

33-40

Volumetric soil water content (%)

was highest beneath hedgerows and remained highest until the end of the cropping season. The topsoil beneath hedgerows contains more macropores than the adjacent alley and this additional pore space is partly accountable for an increased infiltration (Kiepe, 1995), but the extra pore space found in the topsoil was not detected in the subsoil. However, after each rainstorm more water accumulated in the subsoil beneath the hedgerow than in the subsoil beneath the alley for all hedgerow treatments. Hence, there must be a flow path accountable for conducting infiltrated water deeper into the subsoil. Presumably, the surplus of infiltrated water percolated through old tree root channels (Van Noordwijk et al., 1991b), which are often found in the subsoil or along living tree roots.

Despite the faster depletion of soil water beneath the hedgerow in the days after a rain storm, the hedgerow barrier system retained more water than the crop control. This can be deduced from the total storage of water as well as from the total above-ground dry matter production data in the two seasons when high doses of fertilizer were applied. When nutrient competition is eliminated, any increase in dry matter production must be due to a higher content of plant available water. Plots of all treatments had the same water content at the end of both rainy seasons as at the start of the season. Therefore, plant production responses reflected the temporal changes in water availability within the season. Total dry matter production of hedgerow treatment S4 was higher than the crop control in the first season and of treatment D4 and D8 in both seasons. Maize grain yield in treatment D8 was higher than in the crop control for both seasons. Hence, the hedgerow treatments make productive use of water captured by the barrier effect of the hedgerow.

The dynamic aspect of the hedgerow as a living soil conservation barrier becomes apparent when the tree/crop interface is examined (Huxley, 1985). In the early stages of the first season the increase in volumetric water content after a storm was confined to the soil directly beneath the hedgerow. In the course of time, however, the total water stored on either side of the hedgerow barrier was higher than the soil beneath the alley (Fig. 5.6). Thereafter, and during subsequent seasons, both sides of the hedgerow stored more water than the soil beneath the alley. It shows that the below-ground area involved in storing excess water was not confined to the hedgerow, but that the hedgerow-barrier effectively develops a reservoir in the uphill and downhill interfaces.

Expansion of the below-ground biomass of the hedgerow may pose a potential threat to the crop in the form of water competition. However, soil water data revealed that the water content beneath the cassia hedgerows remained higher than beneath the crops until the time of harvest. This meant that the maize did not suffer from water competition. Nevertheless, one has to bear in mind that absence of competition in this case certainly does not apply to all hedgerow species. Severe water competition has been reported for other hedgerow species (e.g. Rao et al., 1991).

5.5 Conclusion

Spatial arrangement of crops and trees in an intercropping system on sloping land has a distinct effect on the spatial distribution of soil water. Infiltration is higher beneath hedgerows than under crops. The soil beneath the hedgerows was recharged with water to

a greater depth than in the alleys, while the total water storage was greater beneath the hedge also. Water that infiltrated beneath the hedgerow was partly available for crop production.

The below-ground area underneath the hedgerow where more water accumulated after a rain storm expanded over time, which means that the below-ground capacity of storing trapped runoff underneath hedgerows increases as the system matures. Anticipated negative effects linked with the below-ground expansion of the hedgerow, particularly water competition, did not arise or were at least compensated in the cassia hedgerow barrier system. Therefore, the overall efficacy of cassia hedgerow barrier systems in storing trapped runoff is expected to increase over time. It is a clear example that the hedgerow barrier technology can be implemented for erosion control in semi-arid areas, too, provided that the tree species involved traps more water than it consumes.

6 Analytical framework for estimating mulch and barrier effects of hedgerows on seasonal runoff and soil loss

Abstract

A framework is proposed for estimating runoff and soil loss in hedgerow barrier systems. Both the effect of hedgerows and of surface mulch of hedgerow prunings are taken into account, allowing prediction of runoff and soil loss for the treatments mulch-only, hedgerows without mulch and hedgerows with mulch. Seasonal runoff is estimated with two parameters that represent the impact of mulch (a_m) and hedgerows (a_h) on infiltration and three variables: mulch-application rate (M), infiltration on the control plot (I_c) and the runoff-rainfall ratio of the control plot (q_c). Seasonal soil loss is estimated using two parameters that represent the barrier effect of mulch (b_m) and hedgerows (b_h) on sediment concentration and three variables: mulch-application rate (M), seasonal runoff (R) and sediment-concentration of runoff (c). The four parameters were obtained from the mulch-only treatment and the hedgerow without mulch treatment, and tested against the hedgerow+mulch treatment. Correlation between estimated and measured values was high during six measurement seasons.

6.1 Introduction

The process of water erosion starts when a raindrop hits the soil surface, dislodging soil particles that are subsequently removed by runoff. This process can be stopped in its initial stage by protecting the soil with a cover, or in a later stage by blocking runoff with barriers. A mulch cover protects the soil against raindrop impact and the many tiny barriers obstruct runoff and increase infiltration (Adams, 1966). Hedgerows obstruct runoff partly through the physical impact of the stem and partly through improved infiltration (Kiepe, 1995). Both interventions, mulch as well as hedgerows, increase infiltration and, consequently, reduce runoff. Moreover, because runoff is the transport agent for dislodged soil particles, controlling runoff means controlling soil loss.

The influence of mulch on soil erosion has been studied extensively, because soil cover is considered to be the dominant factor of all parameters that affect erosion (Wischmeier, 1960; Hudson, 1986). Conversely, the barrier effect of hedgerows on runoff and erosion was studied by few scientists (Chapter 2). So far, quantification of the impact of mulch and barrier effects separately and in combination on runoff and soil loss was described by statistical relations only. This study is an attempt to describe the interactions by a set of algorithms based on physical processes to obtain a tool to design more effective hedgerow barrier systems.

6.2 Materials and methods

6.2.1 The study area

Experimental plots were installed on a 14% slope of the ICRAF Research Station in Machakos, Kenya ($1^{\circ} 33'S$, $37^{\circ} 14'E$) at an altitude of 1600 m. The soil of the experimental plots is a sandy clay loam over a sandy clay, about 150 cm deep and was classified as Chromic Luvisol (Kibe et al., 1981), and updated to Haplic Lixisol (FAO, 1988) or Kanhaplic Rhodustalf (Soil Survey Staff, 1990). From a fertility point of view the soils are low in carbon, nitrogen and phosphorus. Rainfall distribution in Machakos is bimodal. Locally, the rainy seasons are called the long rains (LR) and the short rains (SR) although both seasons qualify as short. There is a large variability in annual and seasonal rainfall and consequently also in rainfall reliability (Braun, 1977). The long rains usually start in the second half of March and last up to two months. The average rainfall in this period is 330 mm (± 155). The short rains start in the second half of October and continue until the beginning of January. The average rainfall of this season is 365 mm (± 125). Another 65 mm (± 50) is falling in scattered showers off-season.

6.2.2 The experimental set-up

Hedgerows of cassia (*Cassia siamea*, Lam.), a non-nodulating leguminous tree, were planted on the contour in two treatments. Trees were planted 0.25 m apart within-row with a hedgerow spacing of 4.0 m, in April 1988 and pruned the first time in March 1989. The hedgerow treatments were: a combination of hedgerows with mulch applied on the alley

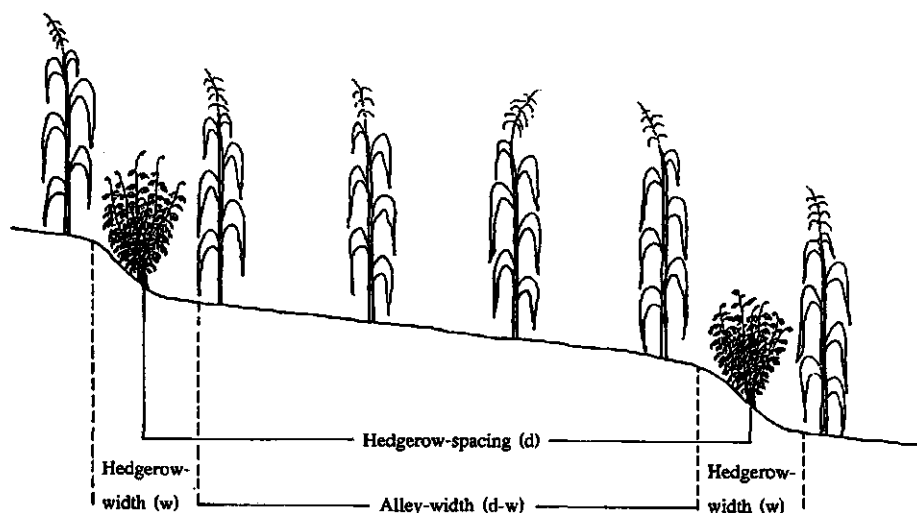


Fig. 6.1 Schematic cross-section through a hedgerow barrier treatment, depicting hedgerow spacing (d), hedgerow-width (w) and alley-width ($d-w$).

(H + M) and a hedgerow treatment (H) where the biomass was carried away, representing a fodder-hedgerow situation. Two treatments without hedgerows were: a mulch treatment (M) that received a seasonal application of tree prunings at the same rate as the first treatment, but from outside the plot, and a control plot (C) which had apart from contour planting no additional soil conservation measures.

Two crops, maize (*Zea mays*, cv. Katumani Composite B) and cowpea (*Vigna unguiculata*, cv. K 80), were grown in rotation from October 1988 onwards. The crop layout was matched with the hedgerows so that no maize row was lost (Fig. 6.1), but cowpea sacrificed 10% of its population. Maize received 40 kg of N and 40 kg of P_2O_5 , while cowpea was not fertilized. All plots were hand-hoed before the onset of the rains and weeds were removed by hand-hoe six weeks after planting. Hedgerows were pruned and mulch was subsequently applied every season before the onset of the rains. Land and crop management were the same for all treatments.

Four runoff plots of 10 x 40 m were installed on a 14% slope, confined by a metal strip of 0.3 m high that was placed across the top of the plot and down the slope to avoid cross-flow. Runoff was intercepted by wash traps at the bottom of the plot and channelled through drain pipes into collection tanks. From March 1990 through March 1993 the total runoff and soil loss were measured every time after an erosion event occurred. Rainfall intensity was measured with a tipping-bucket raingauge and spatial variability within storms was measured with a string of seven standard-WMO 0.127 m raingauges across the plots and linked to two standard-WMO 0.203 m raingauges. After one season of trial runs, the short rains of 1989, runoff of three consecutive storms was measured before mulch was applied, allowing an assessment of the variability between the two plots without hedgerows and between the two plots with hedgerows. The coefficient of variation for runoff was 3% for both combinations, indicating a low spatial variability.

6.3 Analysis of infiltration and runoff¹

Runoff and soil loss were analyzed on a seasonal basis. The influence of dynamic factors like canopy cover, mulch cover and antecedent soil moisture content that greatly affect runoff and soil loss of separate erosion events were not taken into account. The values of these factors can be computed on a daily basis by dynamic simulation modelling, but this kind of data is often not available to account for the required validation and calibration of such a model. The influence of dynamic factors can be diminished by taking an entire cropping season into account.

¹A list of symbols and units of measure is found on p. 115

6.3.1 *The effect of mulch on infiltration*

The effect of prunings applied as surface mulch on runoff is calculated by comparing infiltration of the mulch treatment (I_m in mm) with the infiltration of the control (I_c in mm). Infiltration in a mulch plot is then:

$$I_m = I_c + \Delta I_m \quad (6.1)$$

where ΔI_m (mm) is the infiltration increase in a mulch plot. The increase in infiltration on the mulch plot was assumed to be affected by two variables, the amount of mulch applied and the mulch type. Seasonal variation in the occurrence of erosive rain storms is characterized by dividing runoff from the control plot (R_c in mm) by total seasonal rainfall (P_s in mm), which is called the runoff-rainfall ratio (ρ_c). The effect of surface mulch on infiltration is assumed to be equal to a mulch-type parameter (a_m in $ha^{1/2} t^{-1/2}$), that is related to mulch type, leaves, twigs or stalks, and plant species, and the square root of the mulch-application rate (M in $t\ ha^{-1}$), because soil cover has a nonlinear relation with amount of mulch applied. The increase in infiltration on the mulch treatment can be described as:

$$\Delta I_m = a_m \rho_c I_c \sqrt{M} \quad (6.2)$$

Infiltration in a mulch plot is then:

$$I_m = (1 + a_m \rho_c \sqrt{M}) I_c \quad (6.3)$$

and runoff from the mulch treatment (R_m in mm) can be calculated by subtraction of I_m from rainfall.

6.3.2 *The effect of hedgerows on infiltration*

Contrary to the spatially-uniform infiltration increase under mulch, the infiltration increase in a hedgerow barrier system can be split in an increase on the alley and an increase beneath the hedgerow. The increased infiltration under the hedgerow is on the analogy of equation (6.1) related to the two environmental parameters, ρ_c and I_c , a biological parameter (a_h) that characterizes the improved soil structure beneath the hedgerow plus two variables (w and d) that delineate the spatial layout of the hedgerow barrier system.

The impact of the hedgerow on runoff depends also on runoff amount, which in turn is related to the ratio of the alley width ($d-w$) and the hedgerow spacing (d). This assumption is based on the theory that runoff amount is conserved for the entire runoff event (Rose et al., 1983) and is independent of slope length (Agassi & Ben-Hur, 1991) and slope angle (Bruce-Okine & Lal, 1975). The increase in infiltration under the hedgerow is:

$$\Delta I_h = a_h (d-w) d^{-1} \rho_c I_c \quad (6.4)$$

where a_h is the impact of the hedgerow on infiltration, d (m) is the distance between two successive hedgerows and w (m) is the width of the area underneath the hedgerow (Fig. 6.1).

6.3.3 The effect of hedgerow systems on infiltration

The spatially-weighted infiltration in a hedgerow barrier system (I_{h+a} in mm) can be described on the analogy of equation (6.1) as:

$$I_{h+a} = I_c + \Delta I_{h+a} \quad (6.5)$$

or:

$$I_{h+a} = I_c + \Delta I_a (d-w) d^{-1} + \Delta I_h w d^{-1} \quad (6.6)$$

where ΔI_a (mm) is the infiltration increase on the alley and ΔI_h (mm) the infiltration increase beneath the hedgerow. Without mulch application the infiltration increase is restricted to the area beneath the hedgerow, because there is no significant increase in infiltration on the alley, as compared with the control plot (Kiepe, 1995), so:

$$\Delta I_a = 0 \quad (6.7)$$

The infiltration in a hedgerow barrier system without mulch application is then :

$$I_{h+a} = I_c + \Delta I_h w d^{-1} \quad (6.8)$$

The total infiltration under the hedgerow barrier system is found by combining equation (6.4) with equation (6.8):

$$I_{h+a} = (1 + (a_h (d-w) w d^{-2} \rho_c)) I_c \quad (6.9)$$

Runoff from the hedgerow barrier system (R_{h+a} in mm) can be calculated by subtracting I_{h+a} from P_s .

6.3.4 The effect of mulched hedgerow systems on infiltration

The total infiltration under a hedgerow barrier system where mulch is applied on the alley between the hedgerows (I_{h+m}) can be described as:

$$I_{h+m} = I_c + \Delta I_{h+m} \quad (6.10)$$

where ΔI_{h+m} is the spatially weighted increase in infiltration on the alley with mulch and under the hedgerow. Application of mulch on the alley increases the infiltration in the alley and causes, subsequently, less runoff to reach the hedgerow. To estimate infiltration in a mulched hedgerow system the impact of mulch applied on the alley ($\Delta I_{a(m)}$) must be calculated first, followed by calculating the effect of runoff decrease from the alley on the infiltration ($\Delta I_{h(m)}$) under the hedgerow, or:

$$\Delta I_{h+m} = \Delta I_{a(m)} (d-w) d^{-1} + \Delta I_{h(m)} w d^{-1} \quad (6.11)$$

The increase in infiltration under the mulched alley is calculated by multiplying equation (6.2) with a factor $(\sqrt{d(d-w)^{-1}})$ because the same amount of mulch is now cast on a smaller area $(d-w)$, or:

$$\Delta I_{a(m)} = a_m \sqrt{(d(d-w)^{-1} M)} \rho_c I_c \quad (6.12)$$

Runoff from the mulched alley is reduced by infiltration increase on the alley. On the analogy of equation (6.4), multiplied by the factor $[1 - a_m \sqrt{(d(d-w)^{-1} M)}]$ that was derived from equation (6.12) to take the runoff reduction into account, the infiltration increase under the hedgerow is:

$$\Delta I_{h(m)} = a_h (d-w) d^{-1} [1 - a_m \sqrt{(d(d-w)^{-1} M)}] \rho_c I_c \quad (6.13)$$

and the total infiltration under the hedgerow + mulch treatment (Eq. 6.8) becomes:

$$I_{h+m} = \{I_c + \Delta I_{a(m)} (d-w) d^{-1} + \Delta I_{h(m)} w d^{-1}\} \quad (6.14)$$

or:

$$I_{h+m} = \left[1 + \left[(a_m \sqrt{(d-w) d^{-1} M}) + (a_h (d-w) w d^{-2} [1 - a_m \sqrt{(d(d-w)^{-1} M)}]) \right] \rho_c \right] I_c \quad (6.15)$$

Runoff from the hedgerow + mulch system (R_{h+m} in mm) can be calculated by subtracting I_{h+m} from P_s .

6.3.4 *The effect of mulch, hedgerows and their combination on soil loss*

Soil erosion by water is related to the erosive power and the magnitude of the rainy season, and the vulnerability of the soil under prevailing slope and land use to erosion. Seasonal variation in the recurrence of erosive rain storms was characterized in section 6.3.1 by the runoff-rainfall ratio (ρ_c), while seasonal rainfall was characterized by the magnitude of the rainy season (P_s in mm). The sediment concentration of runoff (c in kg m^{-3}) represents the vulnerability of the soil under prevailing land use to erosion. Soil loss from the control treatment (S_c in t ha^{-1}) can now be described as:

$$S_c = \rho_c 0.01 c P_s \quad (6.16)$$

or,

$$S_c = 0.01 c R_c \quad (6.17)$$

The transport capacity of runoff is proportional to runoff depth and runoff velocity (Bennett, 1974). Physical obstruction by mulch or hedgerows causes a reduction in runoff velocity, which in turn reduces the transport energy and subsequently decreases the sediment concentration in runoff. A barrier-effect parameter (b) is introduced that quantifies the induction of sediment deposition. Soil loss from the mulch treatment (S_m in t ha^{-1}) depends

on the barrier-effect parameter of mulch (b_m in $t\ ha^{-1}$) as well as on the amount of mulch applied, so:

$$S_m = b_m M^{-1} 0.01 c R_m \quad \text{for } M \geq b_m \quad (6.18)$$

where R_m is runoff from the mulch treatment².

Soil loss from the hedgerow treatment (S_{h+a} in $t\ ha^{-1}$) depends on the barrier-effect parameter of the cassia hedgerow and is:

$$S_{h+a} = b_h 0.01 c R_{h+a} \quad (6.19)$$

where b_h (-) is the barrier parameter of the hedgerow and R_{h+a} the runoff from the hedgerow treatment.

In the hedgerow + mulch treatment the sediment concentration of runoff that reaches the hedgerow will be lower than in the hedgerow system without mulch. Also, runoff amount from the mulched alley that reaches the hedgerow will be lower than runoff amount from the hedgerow system. The impact of the barrier will be lower than from the system without mulch. Soil loss in the hedgerow + mulch combination treatment (S_{h+m} in $t\ ha^{-1}$) is:

$$S_{h+m} = b_{h+m} 0.01 c_m R_{h+m} \quad (6.20)$$

where b_{h+m} (-) is the barrier effect of the hedgerow in a hedgerow + mulch system. The sediment concentration of the mulched alley (c_m in $kg\ m^{-3}$) can be described on the analogy of equation (6.18) as:

$$c_m = b_m M^{-1} c \quad (6.21)$$

When the amount of mulch applied increases, the sediment concentration of runoff decreases, hence less sediments can be intercepted by the hedgerow. The barrier effect of the mulched hedgerow is dependent on the effect of the amount of mulch on infiltration, or:

$$b_{h+m} \approx \sqrt{M} \quad (6.22)$$

Soil loss in the hedgerow + mulch combination treatment (S_{h+m} in $t\ ha^{-1}$) can now be described by combining equation (6.20), (6.21) and (6.22) as:

$$S_{h+m} = b_m M^{-1} \sqrt{M} 0.01 c R_{h+m} \quad (6.23)$$

or,

$$S_{h+m} = b_m (\sqrt{M})^{-1} 0.01 c R_{h+m} \quad \text{for } M \geq b_m^2 \quad (6.24)$$

²when $M < b_m$, use: $S_m = \{[M b_m^{-1} (R_m - R_c)] + R_c\} 0.01 c$

Table 6.1 Rainfall (P_s in mm), amount of mulch applied (M in $t\ ha^{-1}$), runoff (R in mm) and infiltration increase (ΔI in mm), the mulch impact on infiltration (a_m) and the hedgerow impact on infiltration (a_h) during six seasons from four treatments at Machakos Research Station.

Treatm.	Control			Mulch			Hedgerow			H + M	
Season	P_s	M	R_c	R_m	ΔI_m	a_m	R_{h+a}	ΔI_{h+a}	a_h	R	ΔI
LR 1990	631	2.00	3.2 ³	2.5	0.7	0.13	1.3	1.9	9.4	0.8	2.4
SR 1990	333	1.16	1.0	0.6	0.4	0.34	0.4	0.6	9.9	0.5	0.5
LR 1991	214	1.33	1.7	0.4	1.4	0.69	0.2	1.5	15.3	0.2	1.5
SR 1991	352	0.83	13.0	4.0	8.9	0.78	0.9	12.1	16.5	0.4	12.6
LR 1992	222	1.63	11.2	0.7	10.5	0.77	0.7	10.5	16.8	0.4	10.8
SR 1992	808	0.80	64.1	30.5	33.6	0.64	17.8	46.3	13.4	9.5	54.6
Mean	427	1.29	15.7	6.5	9.3	0.70	3.6	12.2	13.7	2.0	13.8

where the barrier effect of mulch and hedgerows is equal to the barrier effect of mulch divided by the square root of the amount of mulch applied⁴.

6.4 Results

Infiltration increase was calculated from equation (6.2), (6.4) and (6.11). The season-dependent values for M , P_s and R_c were measured (Table 6.1), the area of increased infiltration was estimated at $w=0.25$ m (Kiepe, 1995) and the hedgerow spacing was $d=4.0$ m. The mulch-type parameter (a_m) was calculated from runoff from the mulch treatment (Table 6.1) using equation (6.2) and the hedgerow-impact parameter (a_h) for infiltration increase was calculated from runoff from the hedgerow treatment (Table 6.1) using equation (6.9). Substitution of the obtained weighted average values $a_m=0.70\ ha^{1/2}\ t^{-1/2}$ and $a_h=13.7$ in equation (6.13) showed a high correlation between the estimated and the measured infiltration increase of the hedgerow + mulch combination treatment ($R^2=0.999$; Fig. 6.2). Subsequent calculation of runoff from the hedgerow + mulch (H + M) treatment by subtracting estimated infiltration in equation (6.15) from rainfall compared favourable with the actual measurements reported in Table 6.1 ($R^2=0.964$; Fig. 6.3).

³Part of the runoff from the control was lost during the major storm of 14 April 1990 and these data were, therefore, not incorporated.

⁴when $M < b_m^2$, use: $S_{h+m} = \{[\sqrt{M} b_m^{-1} (R_{h+m} - R_c)] + R_c\} 0.01\ c$

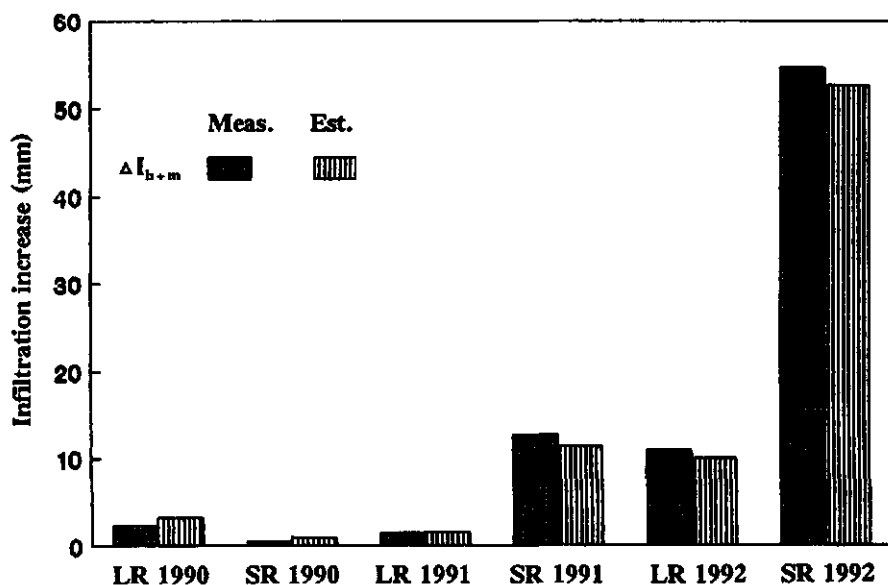


Fig. 6.2 Measured and estimated infiltration increase (ΔI_{h+m} in mm) in the hedgerows + mulch plot for six seasons. ($R^2 = 0.999$).

Table 6.2 Rainfall (mm), soil loss (S in $t\ ha^{-1}$), sediment concentration (c in $kg\ m^{-3}$) and the barrier-effect parameters (b_m and b_h) during six seasons from four treatments at Machakos Research Station.

Season	P	S_c	c	S_m	b_m	S_{h+a}	b_h	S_{h+m}
storm ⁵	52	34.3		4.4		2.2		0.2
LR 1990	579	1.5	46.0	0.1	0.37	0.0	0.08	0.0
SR 1990	333	0.0	1.4	0.0	0.04	0.0	0.04	0.0
LR 1991	214	0.0	0.5	0.0	0.02	0.0	0.05	0.0
SR 1991	352	5.4	41.8	1.1	1.13	0.0	0.07	0.0
LR 1992	222	3.8	33.9	0.0	0.33	0.0	0.05	0.0
SR 1992	808	12.6	19.6	4.1	0.55	1.6	0.47	1.2
Mean	427	9.7	20.9	1.7	0.52	0.7	0.43	0.3

⁵On 14 April 1990 a major storm fell on a nearly saturated soil, which generated a great amount of soil loss.

The sediment concentration was calculated with equation (6.17) from runoff and soil loss data from the control plot (C, Table 6.2). The weighted average was $c=20.9 \text{ kg m}^{-3}$. The weighted average values of the barrier-effect of mulch ($b_m=0.52 \text{ t ha}^{-1}$) and hedgerows ($b_h=0.43$) were calculated respectively from the mulch and hedgerow treatments (Table 6.2) using equation (6.18) and (6.19). Subsequent substitution of b_m and M in equation (6.24) indicated a good correlation between measured soil loss (Table 6.2) and estimated soil loss of the hedgerow + mulch combination treatment ($R^2=0.991$; Fig. 6.4).

6.5 Discussion

Despite the fact that an attempt was made to eliminate the variability of rainstorm energy on a seasonal basis by introducing a runoff-rainfall ratio the infiltration-impact of mulch and hedgerows was still season-dependent. There was a clear difference between the first two seasons in 1990 when both parameters a_m and a_h were low compared with their value in the remaining four seasons. Still, the weighted average of both parameters did predict infiltration and runoff accurately. Presently, it is not known to what extent the values will change for other tree species or different environments. However, it does not seem likely that the impact of hedgerows on infiltration will vary to a great extent. The infiltration-impact parameter of cassia ($a_h=13.7$) was compared with the impact of an adjacent hedgerow barrier of leucaena (*Leucaena leucocephala* (Lam.) de Wit) that was planted four years earlier in a demonstration trial (Kiepe & Young, 1992). It appeared that for leucaena $a_h=13.2$ and that there was no significant difference with the infiltration-impact parameter of cassia. Conversely, it is

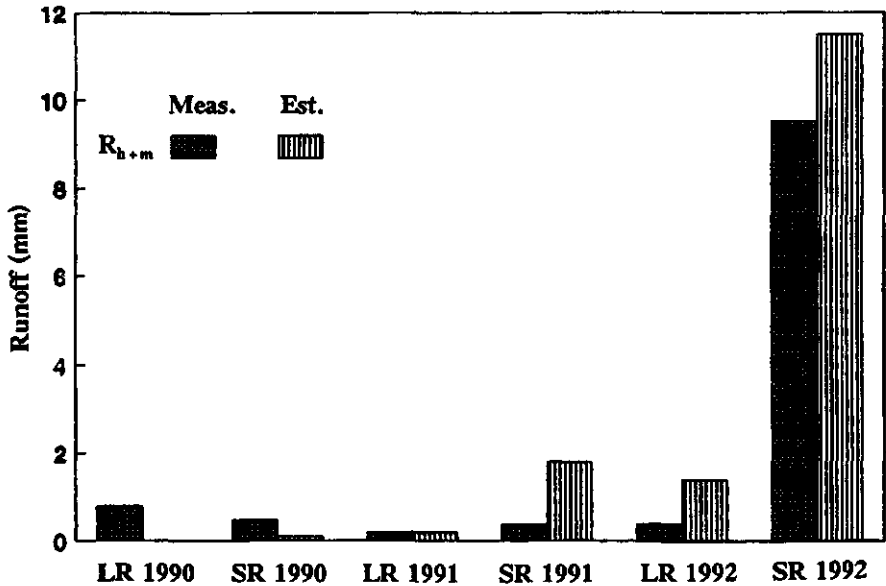


Fig. 6.3 Measured and estimated runoff (R_{h+m} in mm) from the hedgerows + mulch plot for six seasons. ($R^2=0.964$).

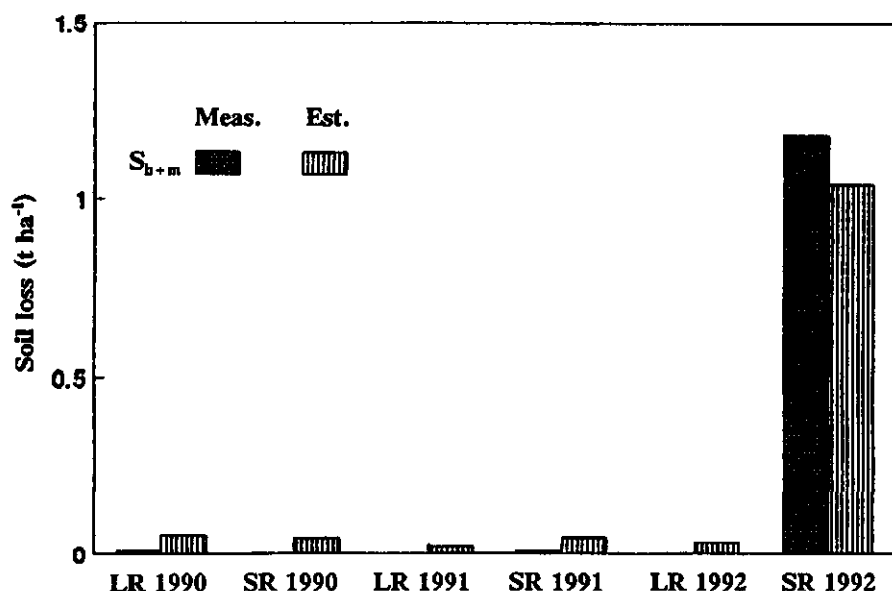


Fig. 6.4 Measured and estimated soil loss (S_{h+m} in $t\ ha^{-1}$) from the hedgerows + mulch plot for six seasons. ($R^2 = 0.993$).

expected that the impact of mulch (a_m) will be subject to a wide range of values, depending on the type and on the species. Application of leucaena mulch in a demonstration trial hardly improved the infiltration on the alley, which indicates that a_m for leucaena is close to zero.

The barrier-effect parameters, b_m and b_h , are subject to environmental and biological adjustments. However, it is not expected that b_m and b_h will change substantially because any change in species or environment is reflected on the runoff parameters first. Nevertheless, it would be worthwhile to test the algorithms presented here for a range of environments and species. If the four parameters, related to mulch and hedgerows, are quantified for a range of tree species and environments, the impact of mulch and hedgerows on a variety of agricultural systems can be calculated easily, provided that erosion and runoff from these systems without soil protection, i.e. the control values, are known.

Estimating the effect of hedgerows and mulch on soil loss requires a value of the vulnerability of the land-use system to erosion first. This land-use parameter (c) embodies a range of land characteristics like slope angle, slope length, soil type and even soil cover. The sediment concentration of runoff and the parameters for the barrier-effect on soil loss were even more season-dependent than the infiltration-impact parameters. However, soil loss was linked to runoff and the weighted average values showed a high correlation. The amount of overestimation is reduced in seasons with little runoff, likewise is the amount of underestimation reduced in seasons with much runoff (Foster et al., 1982). The impact of hedgerows on runoff and soil loss decreases when the amount of mulch applied increases (cf. equations 6.13 and 6.22), likewise it is expected that the impact of hedgerows will increase when the hedgerow distance increases, but that could not be tested in this experiment.

Soil loss in semi-arid areas is dominated by major storms with a recurrence interval of several years. For Machakos it was estimated that these extreme events have a recurrence interval of four years (cf. Chapter 3). During the measurement period such a major storm occurred once, on 14 April 1990. Soil loss was high due to a combination of high rainfall intensity and, simultaneously, a high incident soil water content. The choice was made not to include such a storm in the seasonal soil loss estimates, because it would mean that five out of six seasons would be overestimated. Therefore, it was decided to treat such rare events separately and it seemed a better option to calculate the effect of extreme events with simulation modelling. The combination of rainfall intensity, soil water content and actual soil cover can be included in daily time steps, which provides a more reliable estimate of runoff and soil loss of such rare events. In combination with the recurrence interval of extreme events and the expected seasonal runoff and soil loss (this paper), a detailed description of erosion, and the effect that mulch and barriers impose upon it, can be attained.

6.6 Conclusion

The proposed framework for analysis of the impact of mulch and hedgerows on seasonal runoff and soil loss showed promising results for Machakos. Runoff was accurately estimated with two parameters, one for mulch and one for hedges. Estimated soil loss with the aid of two additional parameters, based on the notion that soil loss is dependent on runoff, was also accurate, except for one extreme event. Testing these algorithms for different tree species, land forms and environments is recommended to obtain a better understanding of the effect of hedgerow barrier systems on erosion control. The proposed analysis also provides a tool to forecast the effects of interventions such as hedgerows, mulch application or a combination of both and could save decades of field trials.

7 Effect of number of tree rows in *Cassia siamea* hedgerows on runoff and soil loss

Abstract

The effect of an increasing number of tree-rows in a *Cassia siamea* hedgerow barriers on runoff and soil loss was measured during four seasons. Ten runoff plots were installed on a 14 % slope of a Lixisol/Alfisol in Machakos, Kenya. Infiltration under hedgerows was related to the number of tree-rows per hedge, infiltration on the cropped alley, the impact of hedgerows on infiltration and the reduction in infiltration increase due to a decreasing impact of each additional tree-row. Soil loss was related to runoff depth, the sediment concentration in runoff and the barrier-effect of hedgerows on sediment deposition. Estimated runoff and soil loss from multiple-row hedges correlated well with measured runoff and soil loss.

7.1 Introduction

Hedgerow barriers have been planted successfully for erosion control (Kiepe & Rao, 1994) but little is known about optimum spatial arrangements. The efficacy of hedgerow barrier systems depends on the spacing between successive hedgerows and the density of the hedgerows (Young, 1989). The density of the hedgerows depends on the spacing between trees within a row, and the number of tree-rows per hedge. Optimal plant spacing within a hedgerow is limited to a narrow range of 0.2-0.3 m. If trees are planted closer together intra-specific competition may get too high resulting in either high seedling mortality or inferior growth. If trees are planted further apart runoff may bypass the area of increased infiltration (Kiepe, 1995) and the hedgerow will not optimally function as an erosion barrier.

Hedgerows are semi-permeable erosion barriers that reduce but do not prevent runoff. A succession of tree-rows increases the resistance to water erosion by reducing runoff velocity and increasing infiltration, thus conserving more water and nutrients for plant production. On the other hand, an increase in the number of tree-rows reduces the arable land ratio of a soil conservation system (Kiepe & Young, 1992) reducing the land available for crop production. Increasing the number of tree-rows also increases the cost of hedgerow establishment (number of trees and labour). Hence, quantification of the relation between the number of tree-rows per hedge and its effect on runoff and soil loss provides a tool for the design of more effective and more cost-effective hedgerow systems as barrier to soil erosion.

7.2 Materials and methods

7.2.1 The study area

The experiment was established on sloping land at the ICRAF Research Station in Machakos, Kenya (1° 33'S, 37° 14'E) at an altitude of 1600 m. The soil of the experimental plots is a

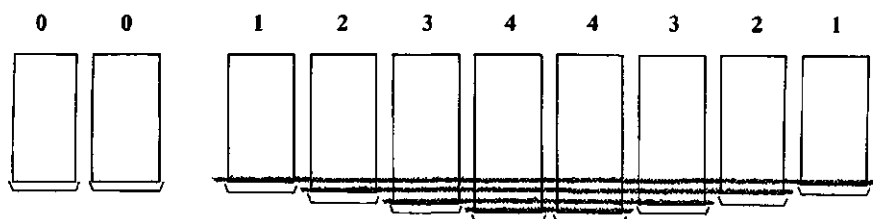


Fig. 7.1 The layout of the experimental plots. The hedgerow treatments are in a symmetric design starting with a hedge of 1 row at both ends, followed by hedges of 2, 3 and 4 rows of trees. The crop-control is located away from the hedgerow treatments. Modified Gerlach troughs are placed at the bottom end of each plot for runoff and sediment collection.

sandy clay loam over sandy clay. The soils are 150 cm deep, classified as Chromic Luvisol (Kibe et al., 1981) and revised as Haplic Lixisol (FAO, 1988) or Kanhaplic Rhodustalf (Soil Survey Staff, 1990). There is a large variability in annual and seasonal rainfall and consequently in rainfall reliability (Braun, 1977). Rainfall distribution in Machakos is bimodal. Locally, the rainy seasons are called the long rains and the short rains although both seasons qualify as short. The long rains (LR) usually start in the second half of March and last through May. The average rainfall in this period is 330 mm (± 155). The short rains (SR) start in the second half of October and continue until the beginning of January. The average rainfall of this season is 365 mm (± 125). Another 65 mm (± 50) is falling in scattered showers off-season.

7.2.2 Experimental design

The experiment incorporates ten runoff plots; five treatments and two replicates arranged on a 14 % slope. The five treatments comprise: four treatments with hedgerows of cassia (*Cassia siamea* Lam.), a non-nodulating leguminous tree, and a control of crops without hedgerow. The four hedgerow treatments consist of an increasing number of tree-rows per hedge: one, two, three and four rows respectively. The control plots were installed away from the agroforestry plots, but located on the same soil type and exactly the same position in the catena. The purpose of splitting the control plots from the agroforestry plots is that tree roots may cause undesirable below-ground interference (Hauser, 1993). Hedgerow plots were planted in October 1988 in a mirror image to minimize interference between treatments, assuming that treatments will be less influenced by adjacent treatments with hedgerows that differ one tree-row than by adjacent treatments with hedgerows that differ several tree-rows (Fig. 7.1). In the single-row hedges cassia trees were planted 0.25 m apart. In hedgerows consisting of two or more tree-rows, parallel successions of single-rows were planted 0.25 m apart in echelon. Hedgerows were pruned just before the onset of each rainy season to a height of 0.3 m. Prunings were weighed, but not applied as mulch. Tree biomass yield was measured for six seasons.

The effect of the number of tree-rows on runoff and soil loss can only receive a fair evaluation if all hedgerows receive the same amount of runoff. To cater for this requirement

the cropping area up-slope from the hedgerows was kept the same size, 5 m wide and 8 m long, and had the same management. The plots were planted with maize (*Zea mays* L., cv. Katumani Composite B) and cowpea (*Vigna unguiculata* (L.) Walp., cv. K 80) in rotation. Maize was fertilized with 40 kg of nitrogen and 17 kg of phosphorus at planting, cowpea was not fertilized. The plots were hand-hoed before the onset of the rains and weeded once by hand-hoe six weeks later.

The amount of runoff at equal distance downslope from the top of each plot can be assumed to be equal for all treatments (Rose et al., 1983). The hedgerow areas were appended down slope to the cropping area. Every tree row was 0.25 m wide and 0.15 m was added between the bottom tree-row and the runoff traps to capture drips from the canopy. The total area of each treatment measured 40.00, 42.00, 43.25, 44.50 and 45.75 m² respectively for the treatments with 0, 1, 2, 3 and 4 hedgerows. These area values were used for conversion and calculation of intercepted rainfall, infiltration, runoff and soil loss. Runoff was trapped by modified Gerlach troughs at the bottom of the plots and channelled through drain-pipes into collection tanks. The runoff collection-equipment, including a 0.3 m high metal confinement around the plots, was installed in 1990 and measurements started in March 1991.

7.3 Analysis

7.3.1 Infiltration

Infiltration under the crop and beneath the hedgerows was calculated by subtracting runoff from rainfall. Assuming that infiltration under the crop is similar for all treatments (Kiepe, 1995) the infiltration on the hedgerow barrier system (I_{h+a} in mm) can be calculated according to Chapter 6 as:

$$I_{h+a} = I_c + \Delta I_{h+a} \quad (7.1)$$

where I_c is the infiltration under the crop (mm) and ΔI_{h+a} (mm) the infiltration increase on the hedgerow-barrier system. The infiltration increase of the system is due to the infiltration beneath the hedge. The infiltration increase can be described as:

$$\Delta I_{h+a} = \Delta I_h w d^{-1} \quad (7.2)$$

where ΔI_h (mm) is the infiltration increase under the hedgerow, d the distance (m) between two successive hedgerows and w the width (m) of the hedgerow, or the zone of increased infiltration. The effect of a single hedgerow on infiltration ($\Delta I_{h(1)}$ in mm) was quantified (cf. Chapter 6) as:

$$\Delta I_{h(1)} = a_h (d-w) d^{-1} \rho_c I_c = h_1 I_c \quad (7.3)$$

where a_h is a parameter that quantifies the hedgerow impact on infiltration, ρ_c the runoff-rainfall ratio of the alley as well as the control, h_1 is a compound parameter that represents the seasonal effect of single-row hedges on infiltration and is, like h_n that represents multiple-row hedges, utilized to avoid long equations.

The effect of a hedgerow with an increasing number of tree rows on infiltration drops for every additional tree row. Hence, the infiltration increase under the second row is multiplied with an infiltration-increase reduction-factor (j). Equally, in hedges of 3 tree rows the infiltration increase under the third tree row is reduced compared with the increase of the second row. The infiltration ($I_{h(n)}$) under a hedge comprising n tree rows can be described as:

$$I_{h(n)} = (j^0 h_n + j^{-1} h_n + j^{-2} h_n + \dots + j^{1-n} h_n) n^{-1} I_c \quad (7.4)$$

and the infiltration under the hedgerow barrier system ($I_{h(n)+a}$) as:

$$I_{h(n)+a} = \{1 + w d^{-1} h_n n^{-1} (j^0 + j^{-1} + j^{-2} + \dots + j^{1-n})\} I_c \quad (7.5)$$

Runoff ($R_{h(n)+a}$ in mm) from hedgerow barrier systems with hedges containing n tree rows is calculated by subtracting the infiltration ($I_{h(n)+a}$) from the rain (P_r).

7.3.2 Soil loss

Soil loss is closely related to runoff. Soil loss from the control plot (S_c in $t\ ha^{-1}$) can be described as (cf. Chapter 6):

$$S_c = 0.01\ c\ R_c \quad (7.6)$$

where c is the sediment concentration in runoff ($kg\ m^{-3}$) that characterizes the vulnerability of the soil under prevailing land use to water erosion. Soil loss under a hedgerow barrier with 1 row of trees (S_{h+a} in $t\ ha^{-1}$) can be described as (cf. Chapter 6):

Table 7.1 Seasonal runoff (mm) from increasingly-wide hedgerows during the long rains (LR) and the short rains (SR) of 1991 and 1992.

Season	Rain (mm)	No. of tree rows				
		0	1	2	3	4
LR 1991	214	1.8	0.9	0.9	0.8	0.9
SR 1991	352	17.5	9.8	9.4	7.4	7.9
LR 1992	222	12.5	7.9	3.1	2.8	1.9
SR 1992	433 ¹	33.3	26.4	23.8	21.5	18.4
Ann. Mean	611	32.6	22.4	18.6	16.3	14.5
CV (%)		2.2	8.5	4.3	3.7	7.0

¹Analysis was stopped after 1 January 1993, while the total rainfall of this season was 808 mm.

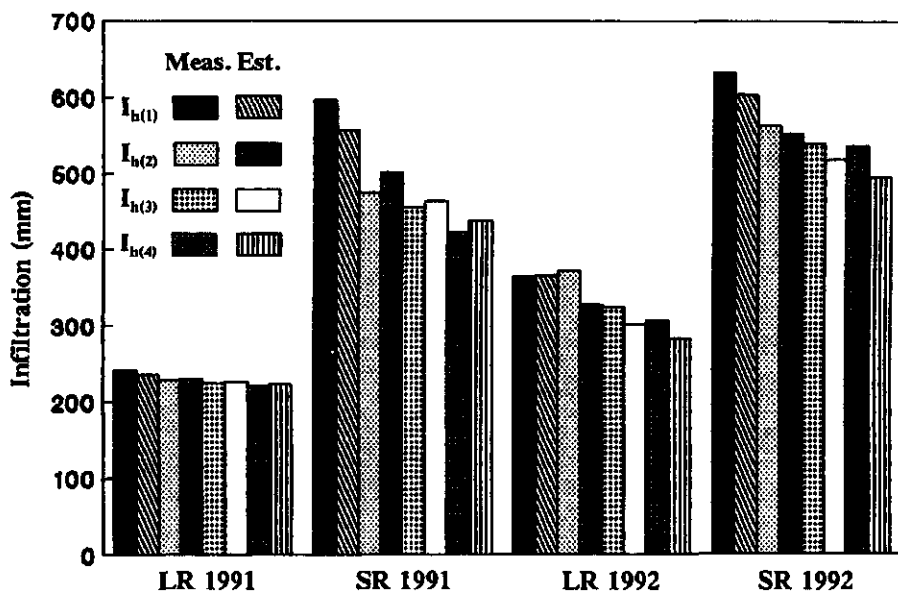


Fig. 7.2 Infiltration under hedges of 1 ($I_{h(1)}$), 2 ($I_{h(2)}$), 3 ($I_{h(3)}$) and 4 rows of trees ($I_{h(4)}$) during four seasons. Correlation between measured and estimated seasonal infiltration under the hedges was high ($R^2=0.978$).

$$S_{h(1)+a} = b_h 0.01 c R_{h(1)+a} \quad (7.7)$$

where b_h is the barrier effect of the hedgerow on sediment deposition and $R_{h(1)+a}$ (mm) runoff from the hedgerow treatment. Soil loss from treatments with hedges of two or more rows of trees ($S_{h(n)+a}$ in $t\ ha^{-1}$) can now be described on the analogy of equation (7.7) as:

$$S_{h(n)+a} = b_{h(n)} 0.01 c R_{h(n)+a} \quad (7.8)$$

where $b_{h(n)}$ is the barrier-effect parameter of the hedge with n rows of trees and $R_{h(n)+a}$ the corresponding runoff.

7.4 Results

7.4.1 Infiltration and runoff

In the first and third season rainfall was below average, in the second and in the fourth season rainfall was about average and well above average, respectively. Unfortunately, in the last season cowpea suffered from root and collar rot causing large differences in crop cover. Therefore, the quantity of runoff from the cropping areas was not similar when reaching the hedgerows. Consequently, the test of the effect of the number of tree-rows was confounded

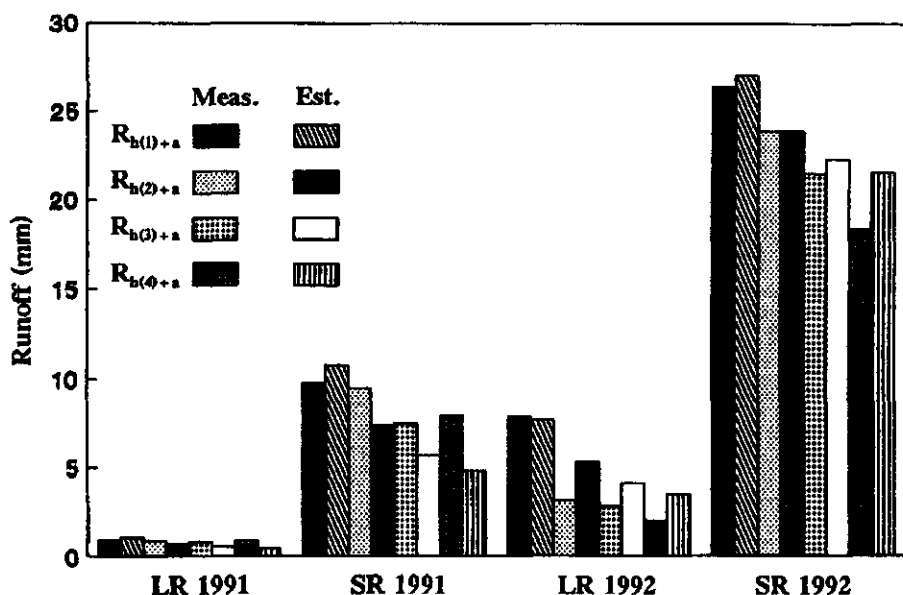


Fig. 7.3 Runoff from hedges of 1 ($R_{h(1)+a}$), 2 ($R_{h(2)+a}$), 3 ($R_{h(3)+a}$) and 4 rows of trees ($R_{h(4)+a}$) during four seasons. Correlation between measured and estimated seasonal runoff under the hedges was high ($R^2=0.970$).

by unequal amounts of runoff. Hence, storms after 1 January 1993 were omitted from the analysis to avoid inaccurate conclusions. Until that time the influence of the crop cover on the amount of runoff was modest. At that time the station had received 433 mm, while the total rainfall at the end of that season was 808 mm.

The impact of cassia hedgerows on infiltration was calculated in Chapter 6 as $a_h=13.7$ and used in equation (7.3), (7.4) and (7.5) to estimate the infiltration under hedges of 1, 2, 3 and 4 tree rows, being 0.25, 0.5, 0.75 and 1.0 m wide. The infiltration-increase reduction-factor was estimated from the data set at $j=2$. Correlation between measured infiltration and estimated infiltration was high ($R^2=0.978$, Fig. 7.2). Runoff was subsequently calculated by subtracting infiltration from rainfall. Correlation between measured runoff (Table 7.1) and estimated runoff was also high ($R^2=0.970$, Fig. 7.3).

7.4.2 Soil loss

Two parameters are needed to calculate soil loss under a hedgerow barrier treatment. First, the sediment concentration of runoff, c , and, second, the barrier effect of hedgerows on sediment deposition, b_h . The value for $b_h=0.43$ was estimated in Chapter 6, while the value for $c=28.6 \text{ kg m}^{-3}$ was estimated from the control. Both values were substituted in equation (7.8). Runoff estimates from equation (7.5) were used in equation (7.8) to estimate soil loss.

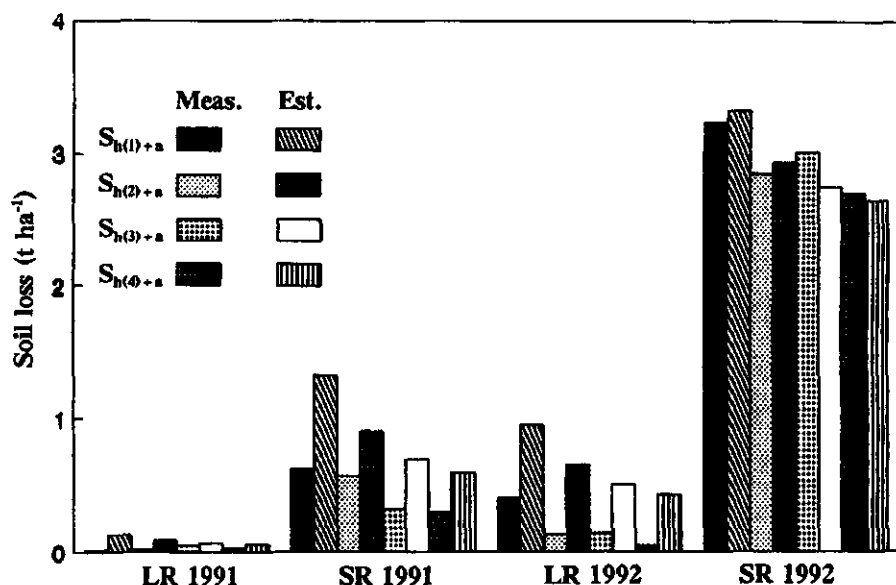


Fig. 7.4 Soil loss from hedges with 1 ($S_{h(1)+a}$), 2 ($S_{h(2)+a}$), 3 ($S_{h(3)+a}$) and 4 rows of trees ($S_{h(4)+a}$) during four seasons. Correlation between measured and estimated seasonal soil loss under hedgerows was good ($R^2=0.930$).

Table 7.2 Seasonal soil loss (t ha⁻¹) from increasingly-wide hedgerows during the long rains (LR) and the short rains (SR) of 1991 and 1992.

Season	Rain (mm)	No. of tree rows				
		0	1	2	3	4
LR 1991	214	0.18	0.02	0.02	0.05	0.03
SR 1991	352	5.11	0.63	0.57	0.32	0.30
LR 1992	222	1.80	0.40	0.14	0.14	0.04
SR 1992	433 ²	4.79	3.23	2.85	3.01	2.70
Ann. Mean	611	5.94	2.14	1.79	1.76	1.53
CV (%)		11.3	2.9	30.1	18.7	12.0

²Analysis was stopped after 1 January 1993, while the total rainfall of this season was 808 mm.

Table 7.3 Seasonal biomass production (oven-dry in kg m⁻¹) from cassia hedgerows during the long rains (LR) and the short rains (SR) of 1990, 1991 and 1992.

Season	Rain mm	No. of tree rows			
		1	2	3	4
LR 1990 ³	631	0.66	0.83	0.89	0.94
SR 1990	333	0.97	1.34	1.62	1.48
LR 1991	214	0.53	0.94	0.98	1.19
SR 1991	352	1.19	1.33	1.98	2.07
LR 1992	222	0.81	0.95	1.35	1.29
SR 1992	808	0.92	1.18	1.54	1.65
Seas. Mean	427	0.85	1.10	1.39	1.44
CV (%)		25	23	13	12

When searching for the relation between $b_{h(n)}$ and $b_{h(1)}$ it appeared that $b_{h(n)} = b_{h(1)}$ gave the best fit. It means that the physical impact of a tree row on the sediment concentration can be assumed to be limited to the first tree row. Apparently, runoff drops the coarse fraction of sediments already at the first impact, while the remaining part is in suspension, so:

$$S_{h(n)+a} = b_h 0.01 c R_{h(n)+a} \quad (7.9)$$

for any number of tree rows. Correlation between measured soil loss (Table 7.2) and estimated soil loss was good ($R^2=0.930$, Fig. 7.4).

7.4.3 Biomass production

Total biomass production of the hedges increased for every additional row of trees, but production per tree declined. Compared with a single-row hedge, a double-row produced 33% more biomass, while hedges with 3 or 4 rows of trees produced 64% and 72% more than a single-row respectively, or 0.85, 1.10, 1.39 and 1.44 kg m⁻¹ hedgerow (Table 7.3). The average biomass production per tree in a hedge containing 1, 2, 3 and 4 rows was 212 g, 137 g, 116 g and 90 g respectively. Although biomass was not measured per tree-row but per hedge it was clearly visible in the field that trees in the middle-rows suffered from intra-specific competition.

³Due to high rainfall cassia was pruned twice this season, but it did not respond well to it.

7.5 Discussion

Four parameters are required for the analysis proposed here to predict soil loss and runoff. Two environmental variables, R_c and c , are needed to characterize climate and soil type. Runoff from the control, R_c , is used as a combined yardstick for the seasonal occurrence of high-intensity rain storms and infiltration of the soil under prevailing land use. The sediment concentration, c , represents the vulnerability of the soil to erosion. The hedgerow parameters a_h and b_h are used to calculate the impact of hedgerows on runoff and soil loss respectively. Apart from these four parameters that are required to calculate the effect of single-row hedges, no additional localized parameters are needed to calculate the effect of multiple-row hedges on runoff and soil loss.

The effect of hedgerow barriers on runoff and soil loss can be raised by increasing the number of tree-rows per hedge. The effect of each additional tree-row in a hedge is a further reduction of runoff and soil loss. However, the spatially-weighted efficacy of the hedge declines for every additional tree-row. From a soil conservation perspective, there are two reasons to prefer single-row to multiple-row hedges. First, because the infiltration increase declines for every additional tree row and, second, because the barrier-effect of hedges on soil loss does not increase with an increase in the number of tree rows. A point in favour of double-row hedges is that the negative effect of a missing tree on erosion control will be less than in single-row hedges. From a plant production perspective multiple-row hedges may be considered as a viable alternative to single-row hedges. When competitive tree species are used in a hedgerow system, crop growth may suffer from resource competition. To minimize competition between crop and hedgerows, hedgerow barriers can be spaced further apart. It is expected that with regard to runoff and soil loss an increase in hedgerow spacing can be compensated when multiple-row hedges are used in stead of single-row hedges.

7.6 Conclusion

When non-competitive tree species are planted for soil conservation a single-row hedge is more effective and cost-effective than multiple-row hedges. However, when competitive tree species are selected hedgerow spacing can be increased to minimize competition between the tree and the crop. This can be achieved without jeopardizing the soil conservation ability of the system by planting multiple-row hedges in stead of single-row hedges. The effect on runoff and soil loss can be calculated with the equations presented in this study. Although research into the potential of hedgerow barriers for soil conservation is presently scanty, it would be interesting to analyze these studies using the same framework. When such a data set becomes available for a range of different slopes, environments and hedgerow species it will certainly add to the successful implementation of hedgerow barriers. However, a combined effort of optimizing the hedgerow spacing for soil and water conservation linked to optimizing plant production can only be attempted with simulation modelling.

8 Effect of spatial arrangement of *Cassia siamea* hedgerows and mulch on runoff and soil loss

Abstract

The effect of single- and double-row *Cassia siamea* hedges on erosion control was tested in 160 m² runoff plots on a 14% slope of a Lixisol/Alfisol at Machakos, Kenya. Runoff and soil loss of single-row hedges spaced 4 m apart (S4) were compared during four cropping seasons with double-row hedges spaced 4 m (D4) and 8 m apart (D8) and tested against a crop control (CC). Maize and cowpea, grown in rotation, sustained in the control an average annual runoff of 47 mm and soil loss of 12 t ha⁻¹. The hedgerow treatments reduced runoff to 8-11 mm and soil loss to 1-2 t ha⁻¹, respectively 17-23% and 12-16% of CC. Plant production of the hedgerow treatments was compared with CC and a tree-control (TC). Differences in crop yields were small, but maize yield in treatment D8 was 10% better than CC, while cowpea yield was 30% lower in treatment D4. Infiltration values were calculated from runoff data using an analytical framework to explain runoff and soil loss. Additional algorithms were added to the framework to account for double-row hedges. Estimated infiltration, runoff and soil loss correlated favourably with calculated and measured data.

8.1 Introduction

The hedgerow barrier technology has been advocated for soil conservation since early this century, while contemporary research is on its way since the end of the 1970's (Kiepe and Rao, 1994). Still, there are presently no guidelines on optimum spatial arrangements with respect to soil conservation or plant production. Recently, a framework was introduced to analyze the impact of mulch and hedgerows on runoff and soil loss (cf. Chapter 6). The framework was tested on single-row hedges planted 4 m apart. However, the effect of spatial arrangement of hedgerows on soil conservation depends on three factors. First, the spacing between individual trees within the tree-rows, second, the number of tree-rows in the hedges and, third, the distance between hedgerows. The first factor, the within-row tree-spacing is restricted to 0.2-0.3 m, leaving little scope for research. If the trees are planted wider, runoff will circumvent the area of higher infiltration (Kiepe, 1995), if the trees are planted closer tree growth will be hampered by intra-specific competition. The second factor, the number of tree-rows within one hedge, can be restricted to single-row and double-row hedges (cf. Chapter 7). The third factor, the distance between hedgerows, will be the subject of this paper. Runoff and soil loss from single-row hedges planted 4 m apart will be compared with double-row hedges planted 4 and 8 m apart.

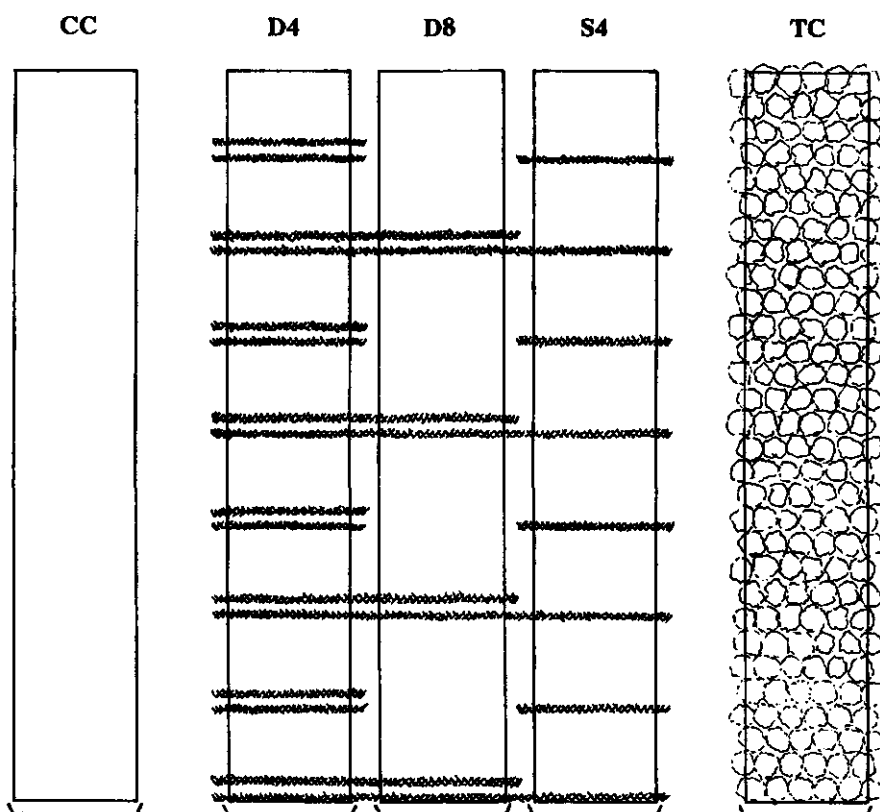


Fig. 8.1 Bird's-eye view of the experimental plots showing the crop-control (CC), tree-control (TC) and three hedgerow treatments; single-line hedgerows planted 4 m apart (S4), double-line hedgerows planted 4 m apart (D4) and double-line hedgerows planted 8 m apart (D8).

8.2 Materials and methods

8.2.1 The study area

The experimental plots were installed at the ICRAF Research Station in Machakos, Kenya (1° 33'S, 37° 14'E) at an altitude of 1600 m. The soil of the plots is a sandy clay loam over a sandy clay, about 150 cm deep and was classified as Chromic Luvisol (Kibe et al., 1981), and revised to Haplic Lixisol (FAO, 1988) or Kanhaplic Rhodustalf (Soil Survey Staff, 1990). Rainfall distribution in Machakos is bimodal. Locally, the rainy seasons are called the long rains (LR) and the short rains (SR) although both seasons qualify as short. There is a large variability in annual and seasonal rainfall and, consequently, in rainfall reliability (Braun, 1977). The long rains usually start in the second half of March and last up to two months. The average rainfall in this period is 330 mm (\pm 155). The short rains start in the

second half of October and continue until the beginning of January. The average rainfall of this season is 365 mm (\pm 125). Another 65 mm (\pm 50) is falling in scattered showers off-season.

8.2.2 Design of the experimental plots

Ten runoff plots of 5 \times 32 m (160 m²) were installed on a 14% slope, five treatments in two replicates. Four treatments were planted in 1989 with cassia trees (*Cassia siamea* Lam.), a non-nodulating legume, while the fifth treatment served as a crop control (CC). In three treatments trees were planted as hedgerows on the contour, while in the fourth treatment trees were planted evenly distributed (TC). Replication of the four treatments with trees is random, but the CC-treatment was located about 50 m away from the cassia treatments to avoid unwanted below-ground interference (Hauser, 1993). All plots were located exactly the same with respect to the catena and distance from the top of the ridge.

The hedgerow treatments were: single-row hedges planted 4 m apart (S4), double-row hedges planted 4 m (D4) and 8 m (D8) apart (Fig. 8.1). The tree spacing within a hedgerow was 0.25 m, while a double-row hedge consisted of two single-rows, planted 0.25 m apart in echelon. Trees in the tree-control plots (TC) were planted 1.0 by 1.0 m in echelon. Trees were pruned each season before the onset of the rains, which is twice a year due to the bimodal rainfall distribution, and the biomass was applied as mulch. The crops, maize (*Zea mays* cv. Katumani composite B) and cowpea (*Vigna unguiculata* cv. K 80) were planted in rotation between the hedgerows and in the crop control. Maize was planted 1.0 by 0.27 m in rows on the contour and cowpea was planted 0.15 m by 0.6 m. No maize row was lost to a hedgerow, but cowpea had to sacrifice 10% of its population. Cowpea was not fertilized, while maize received 200 kg N and 60 kg P for two seasons, to eliminate nutrient competition for a corresponding soil water study. Relative performance of crops and trees is presented as land equivalent ratio's (LER). The LER is a measure of productivity of plants grown in mixtures compared to the productivity of the same species grown in pure stands (Willey, 1979). It is applied here to demonstrate that, apart from a soil and water

Table 8.1 Seasonal and mean annual runoff (mm) from three hedgerow treatments and a crop and tree control at Machakos Research Station.

Season	Rain	CC	D8	S4	D4	TC
LR 1991	214	1.0	0.4	0.8	0.5	0.5
SR 1991	352	13.6	4.7	4.2	2.5	2.3
LR 1992	222	9.2	0.8	1.1	0.8	0.7
SR 1992	808	70.0	15.8	14.6	11.8	13.1
An. mean	798	46.9	10.9	10.3	7.8	8.2
CV (%)		0.2	8.4	13.6	9.7	12.1

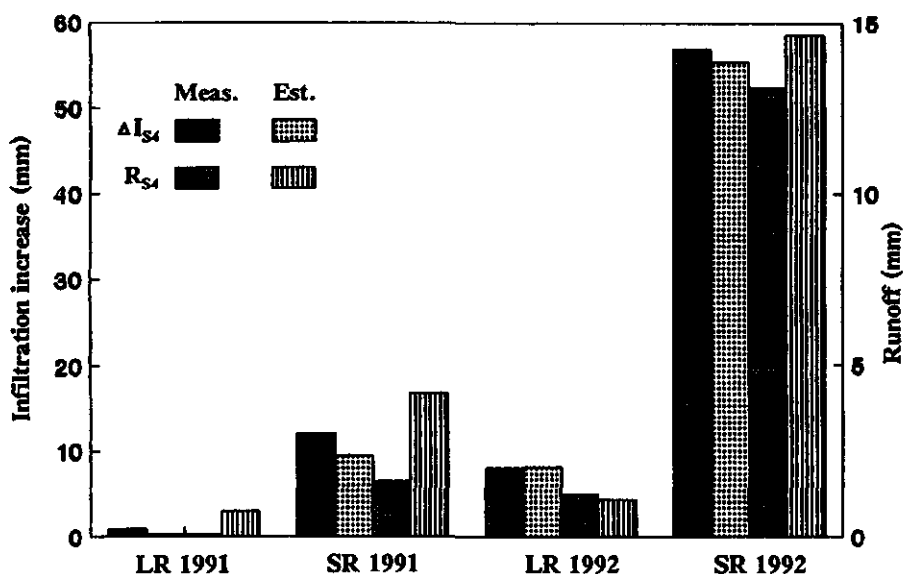


Fig. 8.2 Correlation between measured and estimated infiltration increase (ΔI_{S4} , $R^2=0.997$) as well as measured and estimated runoff (R_{S4} , $R^2=0.951$) in treatment S4.

conservation effect between the hedgerow treatments, there is an effect on plant production. An LER > 1 means that the overall production per unit area increased compared with monocropped treatments. The LER values, together with crop yields, provide an indication of how the infiltrated water is used.

8.3 Results

8.3.1 Runoff and infiltration in treatment S4

Infiltration (I) was calculated from runoff values (Table 8.1), by subtracting runoff (R) from rainfall (P). Infiltration increase in hedgerow barrier systems is partly due to mulch application on the alley and partly due to the presence of the hedgerow barrier. The infiltration under a single-row hedge system planted 4 m apart ($I_{h(l)+m}$ in mm) was described in Chapter 6 as:

$$I_{h(l)+m} = \{1 + [(a_m \sqrt{(d-w)d^{-1}M}) + (a_h w (d-w) d^{-2} [1 - a_m \sqrt{(d(d-w)^{-1}M)}])]\} \rho_c I_c \quad (8.1)$$

where a_m ($\text{ha}^{1/2} \text{t}^{-1/2}$) is the impact of mulch on infiltration in the alley, d (m) is the distance between two successive hedgerows, w (m) is the hedgerow width, M (t ha^{-1}) is the amount of mulch applied, a_h is the impact of the hedgerow on infiltration, ρ_c is the runoff-rainfall ratio of the control and I_c (mm) is the average infiltration under the crop.

Correlation between estimated and measured infiltration increase (ΔI_{S4}), using equation (8.1) and the values $d=4.0$ m, $w=0.25$ m, $a_m=0.70$ and $a_h=13.7$ from Chapter 6 was high ($R^2=0.997$). Runoff from the hedgerow + mulch system (R_{h+m} in mm) can then be calculated for treatment S4 by subtracting I_{h+m} from P_s . Estimated and measured runoff (R_{S4}) showed a good correlation ($R^2=0.951$; Fig. 8.2).

8.3.2 Runoff and infiltration in treatment D4

Infiltration increase under double-row hedges is relatively less than the increase under single-row hedges. The second tree row is clearly less effective in controlling runoff than the first row. Apparently, there is a reduction of the efficacy of the second tree row on the infiltration. The effect of a single-row on infiltration was described in Chapter 6 as:

$$I_{h(1)} = \{1 + (a_h (d-w_1) d^{-1} \rho_c)\} I_c \quad (8.2)$$

According to Chapter 7 infiltration under double-row hedges can be described as:

$$I_{h(2)} = \{(1 + (a_h (d-w_2) d^{-1} \rho_c)) + (1 + j^{-1} (a_h (d-w_2) d^{-1} \rho_c))\} 2^{-1} I_c \quad (8.3)$$

where j is the reduction factor for the additional tree row, w_1 is the width of a single-row hedge and w_2 is the width of a double-row hedge. The effect of the second tree row on infiltration increase was estimated to be half the increase of the first row (cf. Chapter 7). The weighted average infiltration of the double-row hedge system is then:

$$I_{h(2)+m} = \{1 + [(a_m \sqrt{((d-w)d^{-1} M)} + (0.75 a_h w (d-w) d^{-2} [1 - a_m \sqrt{(d(d-w)^{-1} M)}])]\} \rho_c\} I_c \quad (8.4)$$

Estimated and measured infiltration increase using equation (8.4), based on the fit $j=2$, with $w=0.5$ m showed a high correlation ($R^2=0.9997$), while subsequently estimated and measured runoff showed a high correlation too ($R^2=0.993$).

Table 8.2 Seasonal and mean annual soil loss ($t\ ha^{-1}$) from three hedgerow treatments and a crop and tree control at Machakos Research Station.

Season	Rain	CC	D8	S4	D4	TC
LR 1991	214	0.02	0.00	0.02	0.01	0.01
SR 1991	352	1.99	0.47	0.51	0.42	0.47
LR 1992	222	1.40	0.02	0.01	0.01	0.03
SR 1992	808	20.53	3.29	2.49	2.41	2.83
Mean An.	798	11.97	1.89	1.52	1.43	1.67
CV (%)		6.8	5.8	12.8	18.8	2.4

8.3.3 Runoff and infiltration in treatment D8

Runoff depth is linear related to slope length (Rose et al., 1983). Increasing the distance between hedgerows means that the total runoff discharge from the alley increases. There is a positive correlation between the amount of runoff reaching the hedgerow and the subsequent hedgerow-impact on infiltration (cf. Chapter 6), or, a_h increases when runoff amount increases. In the experimental setup used here the effect of alley width on infiltration and runoff could not be tested properly, because there are only two alley spacings (4m and 8m). For the 8 m wide alley an increase by a factor 1.33 was found to make the best fit. Correlation between fitted and measured infiltration ($R^2=0.996$) and runoff ($R^2=0.952$) with $d=8.0$ m and $w=0.5$ m was then at best.

8.3.4 Soil loss from hedgerow treatments

Soil loss in mulched hedgerow systems (S_{h+m} in $t\ ha^{-1}$) was described in Chapter 6 as:

$$S_{h+m} = b_{h+m} 0.01 c_m R_{h+m} \quad (8.5)$$

where b_{h+m} is the barrier effect of hedgerows in a hedgerow + mulch system, c_m ($kg\ m^{-3}$) is the sediment concentration of runoff from a mulch plot and R_{h+m} (mm) is the runoff. In case of multiple-row hedges equation (8.5) can be described as:

$$S_{h(n)+m} = b_{h(n)+m} 0.01 c_m R_{h(n)+m} \quad (8.6)$$

where $b_{h(n)+m}$ is the barrier effect of multiple-row hedges. On the analogy of b_{h+m} in Chapter 6 it can be postulated that the barrier effect of the hedgerow decreases with mulch increase on the alley. Multiple-row hedges produce more mulch than single-row hedges. Therefore, the effect of multiple rows decreases the barrier effect. On the other hand, when the hedgerow distance increases the effect of mulch decreases, increasing the barrier effect, so:

$$b_{h(n)+m} = 2 \sqrt{n\ d^{-1}\ M} \quad (8.7)$$

where n is the number of tree rows, d (m) is the distance between the hedgerows and $2\ (\downarrow 4)$ is added because the reference hedgerow distance of Chapter 6 is 4m. The sediment concentration from the mulch plot was described in Chapter 6 as:

$$c_m = b_m M^{-1} c \quad (8.8)$$

where b_m is the mulch effect on soil loss, M ($t\ ha^{-1}$) is the amount of mulch applied, c ($kg\ m^{-3}$) is the sediment concentration of runoff from the control plot. Soil loss from multiple-row hedges when mulched ($S_{h(n)+m}$ in $t\ ha^{-1}$) can be described by combining equations (8.6), (8.7) and (8.8)¹:

$$S_{h(n)+m} = b_m 2 \sqrt{(n\ d^{-1}\ M^{-1})} 0.01 c R_{h(n)+m} \quad \text{for } M > 4\ n\ d^{-1}\ b_m^2 \quad (8.9)$$

¹for $M < 4\ n\ d\ b_m^2$, use: $S_{h(n)+m} = \{[\sqrt{(M\ d\ n^{-1})}(2\ b_m)^{-1} (R_{h(n)+m} - R_c)] + R_c\} 0.01\ c$

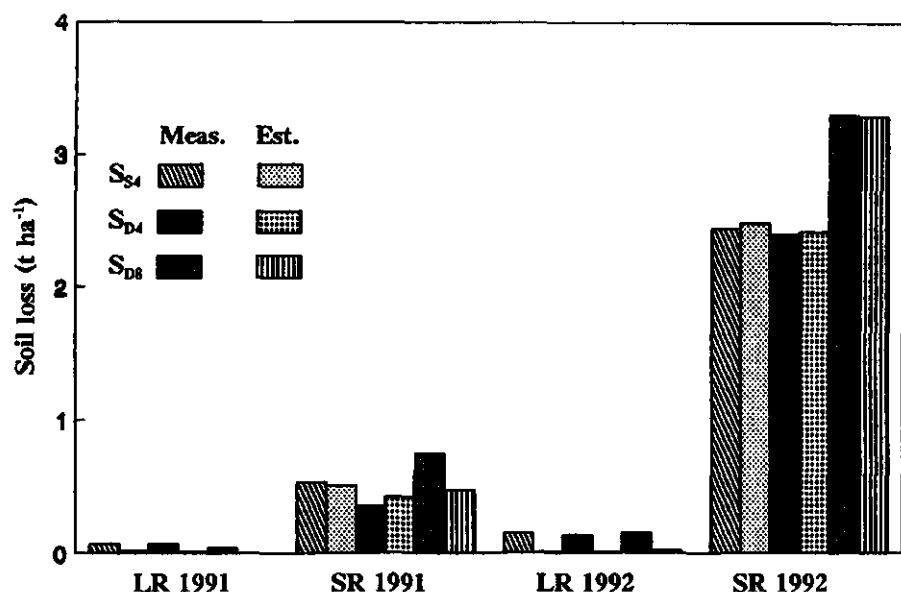


Fig. 8.3 Correlation between measured and estimated soil loss from treatment S4 (S_{S4}), D4 (S_{D4}) and D8 (S_{D8}), ($R^2=0.991$).

The value $b_m=0.52$ was taken from Chapter 6. The sediment concentration of runoff (c) was obtained from the control plot, using data from Tables 8.1 and 8.2, and was estimated $c=28.6 \text{ kg m}^{-3}$. Estimated and measured soil loss (Table 8.2) using equations (8.4) and (8.9) showed a good correlation ($R^2=0.991$; Fig. 8.3).

Table 8.3 Oven-dry grain yields (t ha^{-1}) of two crops from three hedgerow treatments and a crop control at Machakos Research Station.

Season	Rain	Crop	CC	D8	S4	D4
LR 1991	214	cowpea	0.60	0.50	0.46	0.34
SR 1991	352	maize	2.55	2.80	2.63	2.59
LR 1992	222	maize	2.14	2.37	1.96	1.97
SR 1992	808	cowpea	0.27	0.33	0.36	0.22
Mean	511	cowpea	0.44	0.41	0.41	0.28
Mean	287	maize	2.35	2.59	2.30	2.28
CV (%)			4.8	7.5	0.5	1.3

Table 8.4 *L.E.R. of Cassia siamea intercropped with cowpea and maize under three spatial hedgerow arrangements (both crops average of two seasons).*

	D8	S4	D4
Cowpea	0.93	0.93	0.64
Biomass	0.16	0.26	0.38
Maize	1.10	0.98	0.97
Biomass	0.16	0.25	0.36
LER-cowpea	1.09	1.19	1.02
LER-maize	1.26	1.23	1.33

8.3.5 Plant production in hedgerow treatments

Next to soil conservation, an advantage of growing leguminous hedgerows in between crops is the maintenance or increase in soil fertility through decaying tree prunings. However, this advantage was erased in the experiment by the use of a high amount of fertilizer applied to eliminate nutrient competition for a corresponding study into water competition. Nevertheless, crop yield and tree biomass figures are presented here to illustrate that crop production did not suffer from water competition despite two poor rainy seasons. Yield data show that differences are small (Table 8.3). Two outstanding features observed were that treatment D4 had an adverse effect on cowpea yield, but treatment D8 had a positive influence on maize yield (Table 8.4).

8.4 Discussion

Seasonal runoff and soil loss from single-row hedges planted 4 m apart were estimated accurately with an analytical framework presented earlier. Infiltration increase per unit area under double-row hedges is less prominent compared to single-row hedges, which was in agreement with earlier findings. Regarding hedgerow spacing it was noticed that the effect of a double-row hedge on runoff increased again when the alley width increased. However, a clear relation between hedgerow distance and infiltration increase could not be established, because merely two hedgerow spacings are not enough to analyze this effect properly.

During four cropping seasons the crop control sustained an average annual runoff of 47 mm. Runoff from the hedgerow treatments was low and there was little difference between treatments. Treatment D4 reduced runoff to 8 mm, while S4 and D8 reduced runoff to 10-11 mm. Soil loss from the control was 12 t ha⁻¹ and 1-2 t ha⁻¹ from the hedgerow treatments. The values are low and differences not significant. The occurrence of a major storm might clarify differences between treatments but such a storm did not occur in the measurement period.

Differences in crop yields were small. With respect to the LER the 4 m alley treatments were the best, but mostly due to higher tree biomass than D8, which is of relatively-low economic-value compared to crop grains (Table 8.4). With respect to crop yields treatment D8 was better and the fact that in treatment D4 twice as many trees were planted than in S4 and D8, the D8 system would probably come out as the best choice of the three hedgerow barrier arrangements studied. Moreover, with regard to seedling mortality the effect of a missing tree in a double-row is not as bad as a missing tree in a single-row. If the survival rate of seedlings on farms is taken into account, which is definitely lower than on a research station, it is safer to plant a double-row hedge than a single-row. Double-row hedges can be spaced further apart than single-row hedges, which implies easier land management and less interference between tree and crop, an important issue if a more competitive species than cassia is used. The choice of hedgerow species depends mainly on three motives: maximising soil conservation, minimising plant competition and socioeconomic considerations of the land user. This paper deals with soil conservation only, but the other two motives play an equally or even more important part in the design procedure.

8.5 Conclusion

Three hedgerow arrangements were tested for erosion control and plant production. It appeared that the system where double-row hedges were planted 8 m apart had the best perspective. Although not the best conservation system, runoff and soil loss were reduced to satisfactory levels, while crop production was highest. Analysis of the impact of hedgerows showed that runoff and soil loss can be estimated accurately by calculating the infiltration under the crop in the alley and under the hedgerow separately. Runoff and soil loss from hedgerow barrier systems was influenced by the number of tree-rows per hedge and the hedgerow spacing. Additional algorithms to an earlier presented analytical framework showed promising results, but more research is needed to quantify the effect of hedgerow spacing on runoff and soil loss. Also the use of different hedgerow species and environments are worthwhile to be studied and subsequent analysis using the proposed framework is encouraged, so that the range of applicability of the framework will be increased.

9 Principles of modelling soil and water conservation in hedgerow barrier systems

Abstract

A process simulation model called SHIELD (Simulation of Hedgerow Intervention against Erosion and Land Degradation) was developed to compute the effect of hedgerow barriers on runoff, soil loss and crop yields. The model computes runoff and soil loss in daily time steps and uses an existing crop growth model to calculate water uptake, growth and crop yield under conditions without nutrient constraints. Crucial additions to the crop growth model are rainfall intensity, rainstorm energy, infiltration rate, hydraulic conductivity, landform, surface storage, mulch application, mulch and crop cover, spatial arrangement of the system and the vulnerability of the soil to erosion.

9.1 Introduction

Models are simplified images of reality. Every systematic description of reality is a model, even if it is a simple algorithm with merely one or two variables or a detailed computer simulation of physical processes over many years. When the term 'model' is used here it refers to the latter. Process-simulation models can be subdivided in empirical models, usually regression models, that are designed to predict and mechanistic models that are designed to explain. Empirical models may be accurate, but can not be extrapolated because they were derived under specified conditions (Rabbinge & De Wit, 1989). Mechanistic models are based on physical relationships and can be applied over a broad range of environments. They are not designed to be accurate but to clarify links between internal processes within systems.

9.1.1 Modelling runoff and soil loss

The time scale is an important feature of any simulation model. Usually, the time scale of the explained variable cannot be smaller than the time scale of the input data. Soil loss models using annual input data can provide fair estimates of long term averages (e.g. Wischmeier & Smith, 1978; Elwell, 1981). Most static environmental factors (e.g. slope length, slope angle, soil texture, etc.) can be included adequately in these models. However, dynamic factors that vary within a year are smoothed into annual averages and, therefore, such models cannot predict erosion events. The concurrence of a low soil cover, a high vulnerability of the soil to erosion and a high-intensity rainstorm causes major erosion events. The occurrence of the vulnerability of the soil to erosion is in Machakos related to the soil water content (Ahn, 1977). The statement that soils are prone to erosion at the start of the cropping season because fields are bare is too simple. In many subhumid and semi-arid areas the soil profile is dry at the start of the cropping season, having an initially-high infiltration rate that absorbs incipient runoff, thus inhibiting soil loss. It is the combination of low soil cover and high soil water content that makes soils vulnerable to erosion. The concurrence

of this combination and the occurrence of high-intensity rainstorms determines to a large extent the magnitude of runoff and soil loss, which cannot be incorporated in annual soil models, but can in simulation models using sufficiently shorter time scales.

9.1.2 Modelling agroforestry

There are two major challenges in modelling agroforestry. First, agroforestry comprises a range of disciplines, which complicates the modelling effort for mono-disciplinary specialists. Secondly, agroforestry is a relatively new science where many processes are not yet fully understood. There are still many lacunas in agroforestry, notably in the tree/crop interface or the zone where both tree and crop are active (Huxley, 1985). Without letting these lacunas inhibit the development of a process-simulation model, lacunas can be temporarily solved by regression equations. As research progresses these 'emergency dressings' can be replaced by solid descriptions of physical processes. For instance, tree performance is not as well documented as crop performance. Agroforestry cannot draw on large databases as agriculture can, with all its information on the physiology and growth characteristics of the major food crops and responses to constraints, like deficiencies in radiation, water or nutrients. This is not so for trees, where most process-based research has concentrated on forest stands rather than individual trees and where the soil is often treated as a single black box. Furthermore, a crop has often one option to respond to environmental constraints, while a tree has several strategies and might even switch in its approach to tackle constraints over the years (Cannell, 1989; Kozłowski et al., 1991). To circumvent lacunas the approach to modelling can be semi-empirical, until more is known about tree behaviour and the interaction with crops.

9.1.3 Modelling hedgerow barrier systems

The agroforestry technology that shows great potential for soil conservation as well as applicability to a wide range of environments is the hedgerow barrier technology (Young, 1993; Kiepe & Rao, 1994). Compared with other agroforestry technologies it has a simple geometry that is easy to describe mathematically, which makes it suitable as starting point for the modelling approach. Modelling is especially wanted for hedgerow barrier systems, because crucial information in its design, like the optimum spacing between hedgerows, is unknown due to the complexity of the processes involved. For instance, in soil conservation the ideal hedgerow spacing depends on a range of biological, edaphic and climatic factors. Even when the ideal spacing for soil conservation is established it is not necessarily the same as the ideal spacing for plant production. Therefore, the optimum spacing of a hedgerow barrier system should be derived with respect to both plant production and soil conservation to obtain a maximum of products with a minimum of water and soil loss.

9.1.4 Linking the hedgerow barrier model to crop growth models

There are two reasons to link a hedgerow barrier model to an existing crop growth model. First, modelling soil and water conservation aspects of hedgerow barrier systems without considering the effect of hedgerows on crop production is imprudent. Water uptake by plants

is an important component of the water balance and essential to compute the water content of the soil. In turn, the water content of the soil is essential to compute the vulnerability of the soil to erosion. Therefore, water uptake by hedgerow and the crop in the alley cannot be omitted. Secondly, it is important to estimate the yield of the crop because a land user will be reluctant to opt for a conservation technology if the economic benefits are negligible. Linking hedgerow barrier system modelling to crop growth models is, therefore, a necessity. However, time scaling is a problem. For crop growth modelling the choice of a daily time step is an obvious as well as a convenient one, because a day represents a natural unit consisting of complete cycles for processes that can be characterized distinctly by environmental parameters (De Wit & Van Keulen, 1987). Flow processes concerning the water balance differ considerably in time scale. Infiltration is most accurately described in seconds (Van Keulen & Van Beek, 1971), while internal drainage can even be modelled on a weekly time basis. Integration of these time-scales is a prerequisite to calculate the water balance accurately. The best compromise seems daily time steps because of the importance of plant-growth related processes and validated parametric modelling of the water balance (Stroosnijder, 1982).

9.2 Model description

The starting-point in the development of SHIELD was that the model should be linked to an existing crop growth model with feed-back between crop growth and water availability. The model structure that was selected was SUCROS2 (Van Keulen et al., 1992), because it is mechanistic, clear and it allows the user to make all necessary changes to adapt it for any required purpose. The tropical maize version of SUCROS2, called MAIZE2 (Stroosnijder, 1989b), became the basis of SHIELD. The last character of the names of both crop growth models indicates Production Level 2 (De Wit & Penning de Vries, 1982). It means that water stress is incorporated, but other stress factors caused by nutrient deficiencies, pests and diseases are not considered. The crop growth model of Production Level 1, that is without any constraint, is SUCROS1 (Goudriaan & Van Laar, 1994). Hence, SHIELD assumes an ample fertilized crop, free of pest and diseases. SHIELD was written in the simulation language FST (Fortran Simulation Translator) that generates a Fortran program and the corresponding data files (Van Kraalingen et al., 1994), which allows the user to work in a Fortran simulation environment. The applicability of the crop growth model was enhanced for use at higher elevations by changing two parameters in the Penman-Monteith combination equation. Necessary changes for modelling runoff and soil loss were a revised water balance and adding a parametric-modelled soil balance. The water balance now includes critical features like infiltration and moisture deficit of the topsoil, which determine Hortonian overland flow, hydraulic conductivity, which determines topsoil saturation overland flow, and surface depression storage. The soil balance was added to the water balance by parametric modelling of the sediment concentration in runoff. The spatial arrangement of crops and hedgerows, the effect of mulch and hedgerows on infiltration and the spatial uptake of water were added to compute the effect of mulch and hedgerows on runoff, soil loss and crop production.

9.2.1 Crop growth at high elevations

The equations used to compute the driving variables for evapotranspiration in SUCROS2 and MAIZE2 are based on sea level values of the parameters used. In order to increase the applicability of SHIELD to higher elevations and cooler temperatures two parameters, the psychrometer constant (γ in kPa K⁻¹) and the volumetric latent heat of vaporization of water (λ in J kg⁻¹ K⁻¹) were replaced by three equations. The psychrometer constant depends on the atmospheric pressure (p in kPa) and the latent heat. The average atmospheric pressure is calculated from its relation with the altitude (Z in m) by the following equation (Pearcy et al., 1989):

$$p = 101.325 [(1 - (2.2569 \cdot 10^{-5} Z))^{5.2553}] \quad (9.1)$$

The parameter for the latent heat of vaporization of water ($\lambda = 2.4 \cdot 10^6$ J kg⁻¹ for 30 °C) was replaced by (List, 1968):

$$\lambda = (2501 - 2.377 T) \cdot 10^3 \quad (9.2)$$

where T (°C) is the daily average temperature.

The psychrometer constant was derived from the following equation (Monteith & Unsworth, 1990):

$$\gamma = p C_p M_a M_w^{-1} \lambda^{-1} \quad (9.3)$$

where C_p (J kg K⁻¹) is the specific heat of air at constant pressure, M_a is the molecular weight of air and M_w the molecular weight of water vapour. The ratio $M_a / M_w = 1.6077$ and $C_p = 1.012 \cdot 10^3$, so the equation will be:

$$\gamma = 1.627 \cdot 10^3 p \lambda^{-1} \quad (9.4)$$

9.2.2 Rainstorm events

In simulation models that use daily time steps with daily rainfall as input runoff can only be taken into account in a simple way. In MAIZE2 an empirical relation between daily rainfall and runoff percentage was used. In reality, the duration of an erosive storm is but a fraction

Table 9.1 Example of converting the actual rainstorm duration to the rainfall duration based on the highest 60-minute intensity.

	Storm depth (mm)	Duration (min)	Intensity (mm h ⁻¹)
Actual	52	226	13.8
60-min intensity	-	-	34.5
Figure used	52	90	34.5

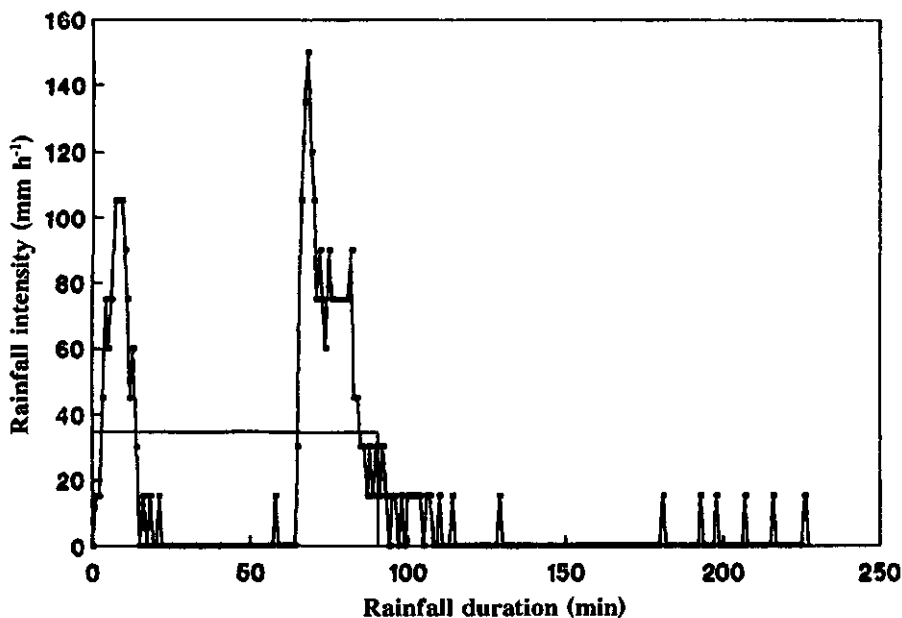


Fig. 9.1 Example of the quantification of a rainstorm into one distinct intensity description.

of a day, taking several hours or less. Therefore, to improve the runoff description in SHIELD a storm-duration input-table was included next to daily rainfall. It enables to restrict rainfall and subsequent infiltration to a fraction of the day. It is assumed that erosive storms occur not more than once a day and that all daily rainfall is part of that particular storm. It is difficult to quantify rainstorms with one parameter because there is a large variation between and even within storms (Peterson & Bubenzer, 1986). The total actual duration of a storm is only meaningful if the average intensity is about constant, which is usually not the case. The duration used in SHIELD is calculated from the highest 60-minutes rainfall intensity to account for periods with drizzles in between. This procedure is called time compression (Reeves & Miller, 1975). For example, the actual duration storm that fell on 14 April 1990 (Fig. 9.1) was 226 min, but the duration based on the 60-minute intensity was 90 min (Table 9.1). The few storms that lasted less than 60 minutes did not have significant dry spells in between, so in this case the average intensity was used.

9.2.3 Infiltration and redistribution

The infiltration is calculated in two steps. The first step uses topsoil characteristics and provides a value for a potential infiltration. The second step takes the characteristics of deeper layers into account, such as a less permeable subsoil, leading to the actual infiltration. The potential infiltration of a rainstorm depends on the moisture deficit of the topsoil, the steady infiltration rate and the duration of the rainfall event. The moisture deficit is assumed to be the difference between the actual soil water content and the saturated water content over

the top 0.10 m of the soil. Rainfall that cannot infiltrate because the rainfall rate exceeds the potential infiltration rate is called Hortonian overland flow. The potential infiltration is limited in turn by the hydraulic conductivity and the water content of the soil below 0.10 m. When the topsoil gets saturated due to a limited flow in the subsoil part of the potential infiltration cannot infiltrate. It remains at the surface and is called topsoil saturation overland flow. Both Hortonian overland flow and topsoil saturated overland flow are temporarily stored in depressions at the soil surface and infiltrate after the rainfall event. If this combined Hortonian and topsoil saturated overland flow exceeds the surface depression storage the surplus disappears as runoff. Water that infiltrates during the rainfall event, the actual infiltration, moves from the topsoil vertically downwards, while the percolation to each soil horizon can be limited by the hydraulic conductivity of that particular horizon.

9.2.4 Depression storage

The amount of water that can be stored in surface depressions (s) is calculated from the slope angle (ϕ), clod angle (σ) and depth of tillage (z_d) (Driessen, 1986):

$$s = 0.5 z_d \sin^2(\sigma - \phi) (\cotan(\sigma + \phi) + \cotan(\sigma - \phi)) (2 \sin \sigma \cos \sigma \cos \phi)^{-1} \quad (9.5)$$

Surface depressions can hold a substantial amount of surface water after tillage, but decline because the clods are broken down due to the force of the rains. An empirical formula is introduced that represents the decline in depression storage:

$$z_d = z_i (1 + \Sigma (0.5 A i^2))^{-1} \quad (9.6)$$

where z_d (mm) is the surface depression, z_i (mm) is the initial surface depression and $\Sigma (0.5 A i^2)$ is the cumulative rainfall energy (cf. section 9.2.9). Mechanical weeding in the cropping season can temporarily increase the surface storage again.

9.2.5 Spatial arrangement of the soil

A hedgerow barrier system can be considered as a repetition of conservation units, of which each unit can be divided horizontally into four zones: the hedgerow, the upper alley, the middle alley and the lower alley, and vertically into a number of horizons (Fig. 9.2). The hedgerow zone (H) is restricted to the area directly beneath the hedgerow, which differs from the alley by higher infiltration rates. The upper (U) and lower alley (L) are part of the tree-crop interface, where both crop roots and tree roots are present, while the middle alley (M) is restricted to the crop. The maximum rooting depth of the crop is z_c (mm) and of the hedgerow z_h (mm). The soil water content θ is calculated for each compartment separately. The four zones form the horizontal basis for runoff modelling. Runoff from the first zone flows onto the second zone as runoff, and so on. Runoff from the last zone is considered as runoff from the system. On the moderately-steep slopes of Machakos the upper alley and the lower alley may be considered identical, so for reasons of simplicity three compartments are sufficient.

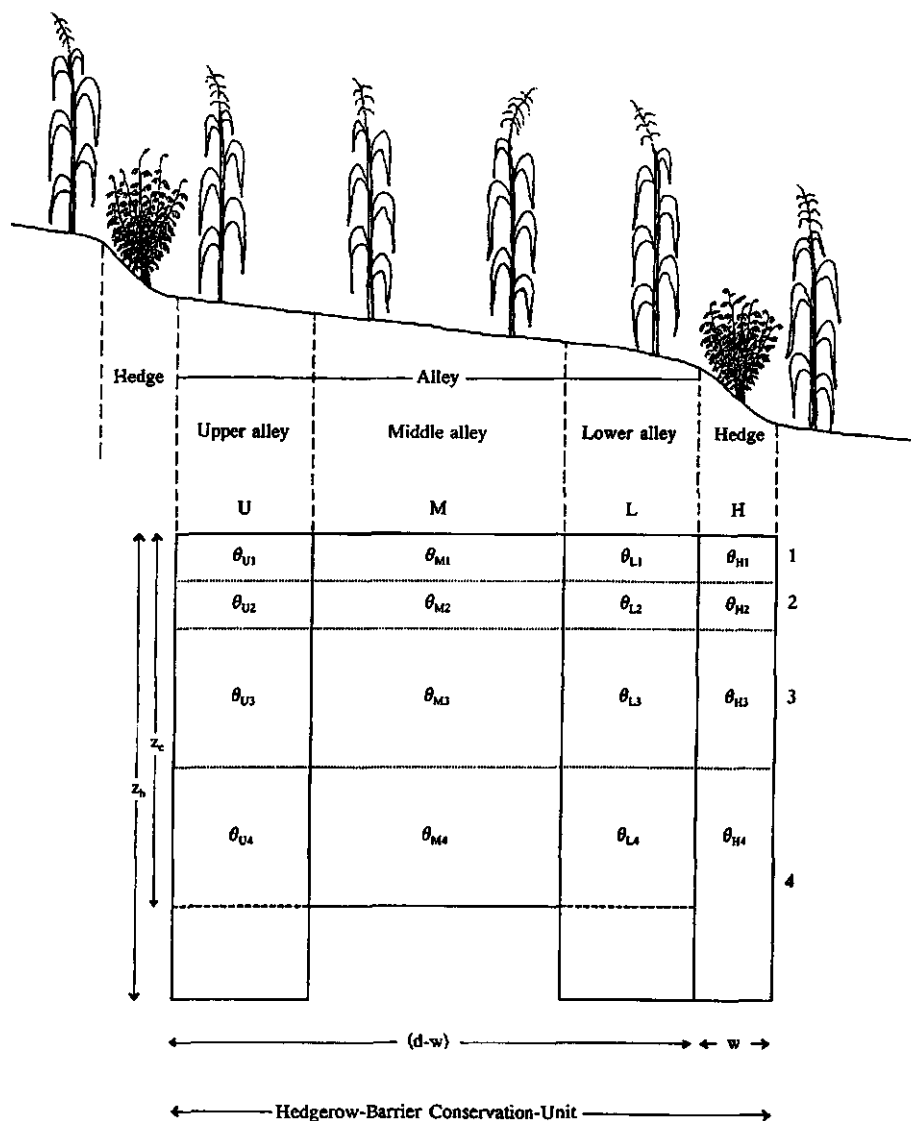


Fig. 9.2 Schematic cross-section through a hedgerow-barrier conservation-unit divided into soil compartments, depicting the upper alley (U), middle alley (M), lower alley (L) and the hedgerow (H), 4 soil horizons (1, 2, 3 and 4), maximum rooting depth of the crop (z_c) and the hedgerow (z_h) and the soil water content θ of each compartment. This cross-section forms the basis of the SHIELD model (Simulation of Hedgerow Intervention against Erosion and Land Degradation).

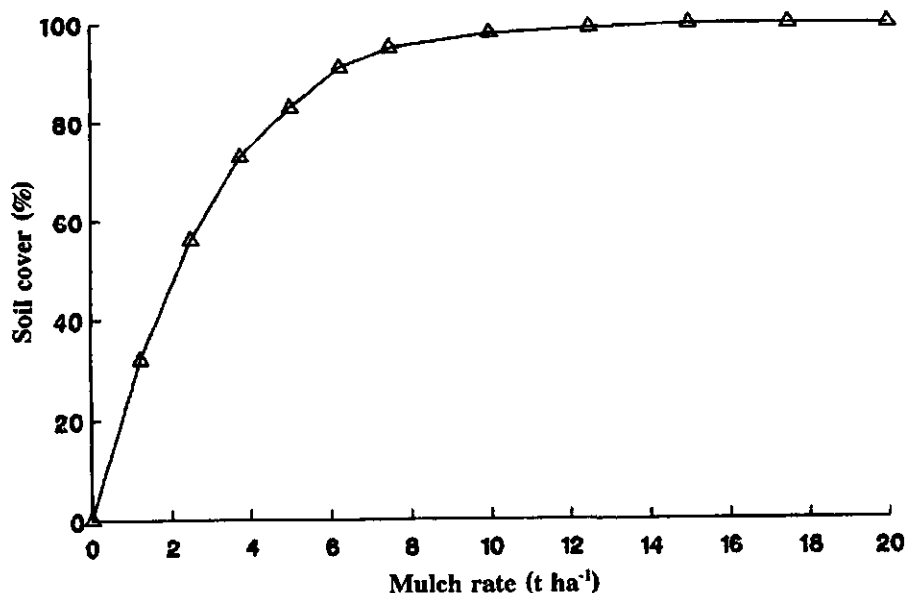


Fig. 9.3 Conversion of the weight of fresh prunings of *Cassia siamea* applied as surface mulch (t ha⁻¹) to soil cover (%) (Average of five readings).

9.2.6 Spatial uptake

Below-ground competition can be a prominent factor in hedgerow barrier systems. Hence, it is important to know where the crop and the hedgerow are taking the water from. Presently, the exact location of water uptake in intercropping situations is not fully understood and, therefore, difficult to model (Thornton et al., 1990). However, new techniques show promising results (Ong & Khan, 1993). In SHIELD it is assumed that there are no tree roots present in the middle alley (M), so plant-available water is for the crop (Fig. 9.2). The crop planted in the upper (U) and lower alley (L) exploits the soil beneath the interfaces (U and L) as well as beneath the hedgerow (H). In turn, the hedgerow exploits the soil directly beneath the hedge as well as the interfaces. Water uptake from the zones with both tree and crop roots present is regulated for each species by a competitive advantage factor for transpiration. Crop yields are computed for each zone accounting for the productivity due to transpiration. The total yield is calculated by spatially weighing the width of each zone with the corresponding productivity.

9.2.7 The effect of mulch on infiltration, runoff and soil loss

The effect of cassia mulch on seasonal infiltration, runoff and soil loss was described in Chapter 6. Accordingly, the effect of mulch on daily infiltration can be described as:

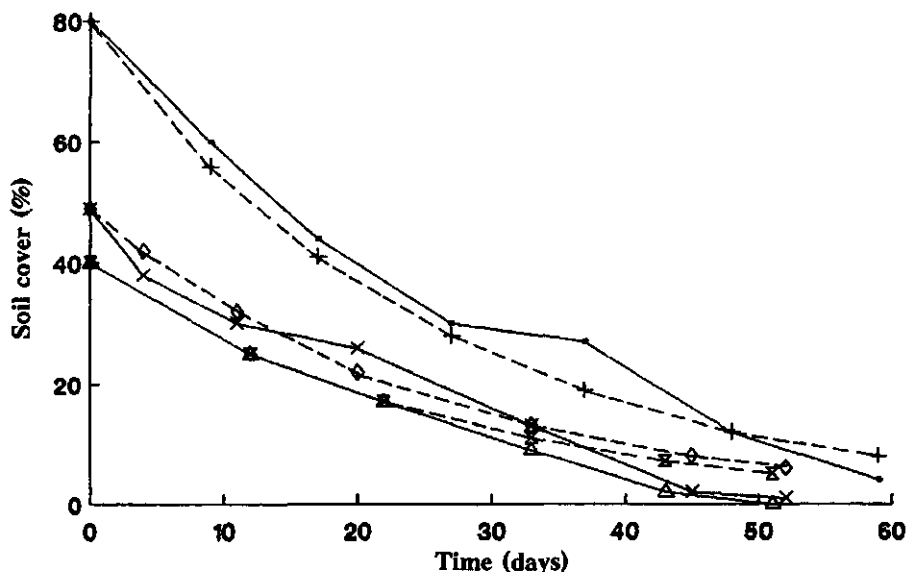


Fig. 9.4 Percentage soil cover of *Cassia siamea* mulch ($F_{m(t)}$) decaying over time (t) for three seasons, measured (—) and estimated (---) according to $F_{m(t)} = F_{m(0)} k^{-t}$ ($k=1.04$; $n=37$, $R^2=0.965$).

$$I_m = (1 + a_m \sqrt{M}) I_c \quad (9.7)$$

where the infiltration in the mulched compartment (I_m) is computed using the mulch-impact parameter (a_m), the amount of mulch (M) and the ambient infiltration (I_c).

In process-simulation modelling the actual soil cover can be calculated daily. First, the conversion from the mulch application rate ($t \text{ ha}^{-1}$) to soil cover (%) needs to be calculated followed by the decay rate. The conversion of the weight of fresh prunings of cassia applied as surface mulch to soil cover (Fig. 9.3) can be described by equation 5 (Gregory, 1982):

$$F_{m(0)} = 1 - e^{-U M} \quad (9.8)$$

where $F_{m(0)}$ is the fraction of soil covered by mulch, U is the specific leaf area of the mulch (ha t^{-1}) and M is the amount of mulch application (t ha^{-1}). For cassia in Machakos a specific leaf area of $U = 0.79 \text{ ha t}^{-1}$ was found for oven-dry leaves ($n = 10$, $R^2 = 0.997$).

The decay rate of cassia mulch can be described by:

$$F_{m(t)} = F_{m(0)} k^{-t} \quad (9.9)$$

where $F_{m(t)}$ is the mulch cover at time t (in days), $F_{m(0)}$ is the initial mulch cover and k is the decay constant. Mulch of fresh tree prunings decays over time due to decomposition. The

rate of decomposition depends on temperature and humidity, as well as plant characteristics, notably the ratio between polyphenolics and nitrogen (Palm & Sanchez, 1991). A decay constant for cassia in Machakos of $k=1.04$ provided a good correlation for six seasons of measurements ($n=37$, $R^2=0.965$; Fig. 9.4).

The effect of mulch on soil loss can be described as (cf. Chapter 6):

$$S_m = b_m M^{-1} 0.01 c R_m \quad \text{for } M \geq b_m \quad (9.10)$$

where soil loss (S_m) is a function of the barrier-effect parameter of mulch (b_m), the amount of mulch applied (M), the sediment concentration (c) and runoff from the mulched compartment (R_m).

9.2.8 The effect of hedgerows on infiltration, runoff and soil loss

The effect of hedgerows on seasonal infiltration, runoff and soil loss was described in chapters 6-8. The algorithms and parameters that were introduced can also be used for the daily infiltration, runoff and soil loss. The sediment concentration in the runoff from the control plot can be estimated (cf. section 9.2.9). The infiltration in hedgerow barrier systems without mulch application for a single-row hedge ($I_{h(1)+a}$) can be calculated according to:

$$I_{h(1)+a} = (1 + (a_h (d-w_1) w_1 d^{-2})) I_c \quad (9.11)$$

and for a double-row hedge ($I_{h(2)+a}$):

$$I_{h(2)+a} = (1 + (0.75 a_h (d-w_2) w_2 d^{-2})) I_c \quad (9.12)$$

where the hedgerow-impact parameter on infiltration (a_h), the distance between the hedgerows (d) and the width of the hedgerow (w_1 or w_2) are required. The infiltration in single-row hedgerow barrier systems with mulch application ($I_{h(1)+m}$) by:

$$I_{h(1)+m} = \{1 + [(a_m \sqrt{(d-w_1) d^{-1} M}) + (a_h (d-w_1) w_1 d^{-2} [1 - a_m \sqrt{d (d-w_1)^{-1} M}])]\} I_c \quad (9.13)$$

and in double-row hedgerow barrier systems with mulch application ($I_{h(2)+m}$) by:

$$I_{h(2)+m} = \{1 + [(a_m \sqrt{(d-w_2) d^{-1} M}) + (0.75 a_h (d-w_2) w_2 d^{-2} [1 - a_m \sqrt{d (d-w_2)^{-1} M}])]\} I_c \quad (9.14)$$

Soil loss of hedgerow barrier systems without mulch application ($S_{h(n)+a}$) can be calculated with:

$$S_{h(n)+a} = b_h 0.01 c R_{h(n)+a} \quad (9.15)$$

where soil loss is a function of the barrier-effect parameter of hedgerows (b_h), the sediment concentration (c) and runoff from the hedgerow barrier system ($R_{h(n)+a}$).

Soil loss of hedgerow barrier systems with mulch application ($S_{h(n)+m}$) is computed by:

$$S_{h(n)+m} = b_m 2 \sqrt{(n d^{-1} M^{-1})} 0.01 c R_{h(n)+m} \quad \text{for } M \geq 4 n d^{-1} b_m^2 \quad (9.16)$$

where soil loss is related to the number of tree rows (n), the hedgerow distance (d), runoff from the mulched hedgerows ($R_{h(n)+m}$) and c , b_m and M .

9.2.9 Sediment concentration in runoff

The proposed parametric modelling of the soil loss uses an estimate of the sediment concentration of runoff first (c in kg m^{-3}), followed by a multiplication with runoff and the hedgerow and mulch barrier parameters. Factors that influence the sediment concentration in SHIELD are: the energy of the storm (E_k), the vulnerability of the soil to erosion (v), landform (LF) and total soil cover (F_T). The dimension found after multiplication of these four factors is not conform to the dimension of the sediment concentration (kg m^{-3}), which is a common problem in establishing a relation between erosive factors and soil loss (Wischmeier & Smith, 1978; Elwell, 1981; Williams et al., 1984; Laflen et al., 1991)). The relation between the factors was quantified with the aid of the following equation, which is only valid for the specific units given in the variable description below:

$$c = E_k v \text{ LF } F_T^{-1} \quad (9.17)$$

9.2.9.1 storm energy

Kinetic energy is defined as half the product of mass and velocity squared. The total mass of a rainstorm equals the amount of rainfall (A in mm), while the velocity equals the rainfall intensity (i in mm h^{-1}). The kinetic energy (E_k in J) of a storm is then:

$$E_k = 0.5 A i^2 \quad (9.18)$$

9.2.9.2 vulnerability of the soil to erosion

The vulnerability of the soil to erosion depends on the cohesive forces that soil particles exert on each other. These forces depend on texture, soil organic matter content and the amount of water in the soil. The effect of texture is that sand and silt increase the vulnerability of the soil to erosion, while clay decreases it (Bouyoucos, 1935; Bruce-Okine & Lal, 1975):

$$(\% \text{ sand} + \% \text{ silt}) (\% \text{ clay})^{-1} \quad (9.19)$$

The effect of organic matter on the resistance of soils to erosion was quantified for the EPIC model (Williams et al., 1984) by a two-lines regression equation. However, it was not quantified for other parts of the world, but the relation is positive (Peterson, 1964). The positive relation between soil organic matter and soil erodibility was also used by Wischmeier and Mannering (1969) in a five-lines regression equation consisting of 24 compound variables. Hence, the relation with vulnerability is taken inversely related to the organic carbon content (C_o^{-1}).

The cohesive forces between soil particles of the Lixisols in Machakos are weakened when water molecules are present between the particles, especially when the water content of the soil is above field capacity. Hence, the amount of water present in the soil profile is of crucial importance. The effect of water in the topsoil is calculated as the antecedent water content divided by the water content at saturation ($\theta_i \theta_s^{-1}$). However, when this factor was incorporated in the formula it still could not explain the high values of sediment concentration during extreme events. When in addition to this factor the cumulative amount of water that infiltrated on the two days preceding a rainstorm (I_p in mm) was incorporated, it appeared that the sediment concentration estimates were satisfactory. Drainage of soil water after a rain storm takes about two days in Machakos, which means that the water present in the soil profile is of crucial importance. An explanation might be the presence of entrapped air, which is caused by flooding or a high intensity rainstorm. Entrapped air can impede infiltration (Linden & Dixon, 1976), but may also cause aggregates to 'explode' (Stroosnijder & Koorevaar, 1972). The vulnerability of the soil to erosion can then be calculated as:

$$v = (\% \text{ sand} + \% \text{ silt}) (\% \text{ clay})^{-1} C_0^{-1} I_p \theta_i \theta_s^{-1} \quad (9.20)$$

9.2.9.3 landform

Landform is defined by shape, slope angle and slope length. A uniform slope loses more soil than a concave but less than a convex slope (Young & Mutchler, 1969; Schmidt, 1992) and is usually taken as reference. The slopes of the trial are uniform, which means that the shape does not affect the soil loss. The relation between slope angle (ϕ in %) and soil loss is exponential and for the tropics the value of 2 is appropriate (Hudson, 1986). Soil loss per unit area decreases with each increase in slope length (Ellison and Ellison, 1947). The effect of slope length on soil loss per unit area is equal to the square root of the length (L in m) (Hudson, 1986). The combined effect on landform (LF in $m^{0.5}$) is:

$$LF = \phi^2 \sqrt{L} \quad (9.21)$$

9.2.9.4 soil cover

A common aspect of most agroforestry technologies is a good soil cover through litterfall or the application of tree prunings as mulch. It is exactly this aspect that gives agroforestry an advantage to agriculture to withstand torrential rains. Hence, it is important to calculate soil cover on a daily basis. The formulas used here were derived from soil cover measurements that were made in a cassia/maize hedgerow barrier trial in Kenya (cf. Chapter 3). Pruned hedgerows of cassia (*Cassia siamea*, Lam.) were planted between maize (*Zea mays*, L., cv. Katumani Composite B) at 4 m distance. Mulch was cast over the alleys at the start of each season at an average rate of 1.1 t ha^{-1} . A distinction was made between mulch cover, crop cover and hedgerow cover. Eventually, stone cover and weed cover were also measured, but when it appeared that both were insignificantly low in Machakos these were left out in later measurements.

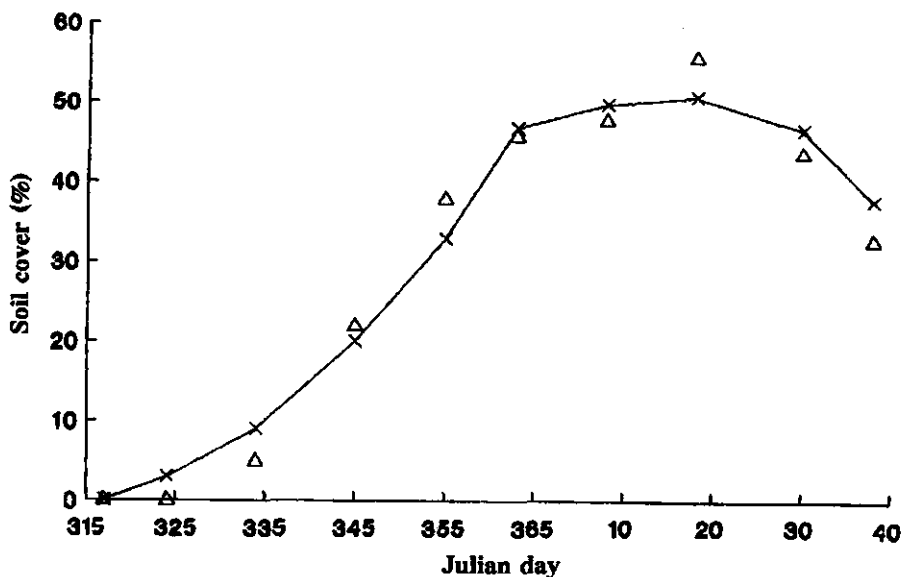


Fig. 9.5 Percentage soil cover of a maize crop ($F_{c(t)}$), measured (x) and estimated from the LAI (Δ). Correlation was $F_{c(t)} = 0.30 \text{ LAI}$ ($n = 10$, $R^2 = 0.966$).

The fraction of soil cover by a maize crop ($F_{c(t)}$) and leaf area index (LAI) were measured for a full season and appeared to be closely related:

$$F_{c(t)} = 0.30 \text{ LAI} \quad (9.22)$$

Correlation was high ($n = 10$, $R^2 = 0.966$; Fig. 9.5). The fraction soil cover by a mulch ($F_{m(t)}$) was described above. The total soil cover ($F_{T(t)}$) is:

$$F_{T(t)} = F_{c(t)} + F_{m(t)} \quad (9.23)$$

9.2.10 Design storm

Criticism from Kiepe (Chapter 3; Chapter 6) on prevailing long-term annual soil loss calculations was that extreme soil loss events could not be calculated. One such an event was the major storm of 14 April 1990 (Julian day 104), when a high-intensity rainstorm fell on a vulnerable soil, which caused considerable soil loss (34.3 t ha^{-1}). The recurrence interval of the storm was estimated at 4 years. With the aid of a SHIELD it is possible to compute the effect when this storm falls in the beginning of the rainy season or at the end, in other words, the effect of the concurrence of simultaneously occurring critical environmental circumstances.

9.3 Discussion

The SHIELD model was developed primarily as an event orientated tool to clarify the effect of hedgerows on runoff and soil loss. The concurrence of low soil cover, high water content and high-intensity rainstorms determines to a great extent the amount of runoff and soil loss. The physical processes that play a crucial role in generating soil loss should then be described in a parametric way with a sufficient level of detail to predict the effect of lay-out and management factors on soil and water losses. A greater level of detail can be achieved by describing the rate of sediment detachment by rainfall, deposition and entrainment by runoff for each particle-size class separately (Rose, 1993), but such a detailed analysis is considered outside the scope of this study. A second aim is that SHIELD may be developed as a tool to compute the optimum hedgerow distance, but to do so, extensive testing on a range of slope classes in various agro-ecological zones is required.

The accuracy of a model depends on how precisely the employed physical processes are known and how precisely these processes are described by mathematical equations (Williams et al., 1991). Despite the many advantages of simulation modelling, a weak point remains that a mechanistic model is sensitive to certain parameters. A slight deviation from an exact factor may lead to over- or underestimation of the crop performance with consequences for evaporation, transpiration and soil cover (Goudriaan, 1993). This is particularly so for potential growth models. It is, therefore, important to validate and calibrate the crop growth model accurately. Models of Production Level 2 are more robust, because of the many feedback factors involved. When the time scale of a model prevents the use of an adequate mathematical description parametric modelling can be attempted instead. However, parametric modelling needs to be validated too. Although accuracy is not the aim of the model, large deviations from the anticipated outcome by whatever reason may cause that the model and its performance lose credibility, at least for modelling opponents. However, in this particular case the exact outcome of the model is not the most important issue, but the optimum lay-out between trees and crops is.

9.4 Conclusion

Soil cover by crop, mulch and hedgerows can be described accurately by a set of time-based equations and can be incorporated in simulation models. Together with soil water content and the occurrence of high-intensity rainstorms, the three major dynamic determinants for runoff and soil loss are characterized. This will elucidate the runoff and erosion process, which may help to design more efficient and productive biological conservation systems, because positive effects of conservation can be balanced with potential negative effects of competition. It provides an important tool to estimate the optimal spatial arrangement of trees in between crops based on a clear choice of the risk one is willing to take. For this the design storm and the concurrence of the design storm with the vulnerability of the soil to erosion are needed and should be tested with 20-season time series. Modelling allows optimum use of large existing data bases that are otherwise not fully exploited. Dynamic simulation should finally be used to indicate weak points in knowledge and thus help to set the research agenda.

10 Applications of modelling soil and water conservation in hedgerow barrier systems

Abstract

A recently developed simulation model called SHIELD computes runoff and soil loss from mono-cropped maize as well as cassia/maize hedgerow-barrier systems. The design storm concept to test soil and water conservation measures was evaluated with SHIELD and judged as inaccurate. It is proposed to use the concept of design event that takes corresponding soil conditions and land management into account. The effect of depth and frequency of tillage on runoff and soil loss were computed and evaluated. Hedgerow distance, density and the application of prunings as surface mulch were used to compute runoff, soil loss and crop yields for 20 consecutive seasons. The hedgerow distance regarding tolerable soil loss criteria was evaluated taking the hedgerow density and the application of mulch into account.

10.1 Introduction

The strength of mechanistic simulation modelling is fourfold. First, complicated processes can be made transparent providing a suitable teaching and research tool. It reveals critical interactions that can lead to a better understanding of the processes involved and, therefore, to more effective research. Secondly, information from previous research of various disciplines can be incorporated and combined, which means a cost-effective way of using earlier research findings. Thirdly, conditions can be simulated with little chance of occurrence in a measurement period. And, fourthly, dynamic simulation modelling can reveal knowledge gaps and, therefore, assists to set the research agenda. A sensitivity analysis is the evident way to reveal critical processes and interactions of complicated systems, while examples of the incorporation of previous research findings can be found in Chapter 9. Three applications will be described here as illustration of the potential of SHIELD (Simulation of Hedgerow Intervention against Erosion and Land Degradation) to analyze the water erosion process. The first application is the evaluation of the suitability of the design storm concept to examine soil and water conservation measures. The second application is to evaluate the effect of tillage on runoff and soil loss. The third application is the evaluation of the optimum distance between hedgerow barriers regarding tolerable soil loss limits.

Soil and water losses from hedgerow barrier systems increase when the distance between hedgerows increases. The maximum distance can be determined by calculating the maximum amount of soil loss allowed without deterioration of the productivity. The criterion, called soil loss tolerance, is based on the rate of soil formation. The value is difficult to measure, because it concerns such a slow process and the values that are reported are generally quite different. In the geomorphological approach the soil loss tolerance is calculated from the weathering rate. However, there is a distinct difference between soil and weathered rock, and thus in the formation rate. Loss of organic matter and organic nutrients, like nitrogen, are at least as important as the loss of inorganic nutrients (Kirkby, 1980). Another problem is

that it is hard to distinguish between geological erosion and man-induced erosion. In Machakos, Kenya, the geomorphological weathering rate was estimated at $5.6 \text{ t ha}^{-1} \text{ y}^{-1}$ (Ahnert, 1982), while the rate of soil formation based on the chemical weathering solution found in rivers was estimated for semi-arid Kenya at less than $0.1 \text{ t ha}^{-1} \text{ y}^{-1}$ (Dunne et al., 1978). Soil loss tolerance values for the USA were estimated in the early 1960's by scientists from various disciplines at 4.5 to $11.2 \text{ t ha}^{-1} \text{ y}^{-1}$ depending on the soil type (Wischmeier & Smith, 1978), while soil formation for Europe was estimated at $1 \text{ t ha}^{-1} \text{ y}^{-1}$ (Troeh & Thompson, 1993). In general, $11 \text{ t ha}^{-1} \text{ y}^{-1}$ is taken as tolerable soil loss (Morgan, 1986), which seems too high a standard considering the low rates of soil formation. Particularly, in tropical areas, when soils are shallow or highly erodible soil loss values of $2\text{--}5 \text{ t ha}^{-1} \text{ y}^{-1}$ are preferred standards (Hudson, 1986). Hence, a target value between 2 and $5 \text{ t ha}^{-1} \text{ y}^{-1}$ seems more realistic for Machakos than $11 \text{ t ha}^{-1} \text{ y}^{-1}$, although it may be still too high to stop land degradation. In fact, most rates that are currently used as erosion standard are too high to support sustainable agriculture (Lafren et al., 1990).

10.2 Materials and methods

10.2.1 The SHIELD model

The four seasons of runoff and soil loss data that were used to calculate the effect of hedgerows and mulch on seasonal runoff and soil loss (cf. chapters 6-8) were subsequently used to validate and calibrate SHIELD, but this time on an event basis. First, the crop growth module MAIZE1 (Stroosnijder, 1989a) was validated in the short rains of 1991 and the long rains of 1992, when maize (*Zea mays*, cv. Katumani Composite B) was planted for two consecutive seasons. Next to the runoff plots, which were described in Chapter 8, there was a sloping rainfed maize plot and an irrigated maize plot on level land. For two seasons, these two maize plots were used to establish the crop characteristics required to validate the parameters for the crop growth module of SHIELD. All plots were fertilized with 200 kg of nitrogen and 60 kg of phosphorus, because the Production Level of SHIELD is 2, i.e. with ample nutrients (cf. Chapter 9). From each plot every ten days five plants were harvested, measured and weighed for carbohydrate allocation. Row by row harvesting of maize in the hedgerow barrier plots showed that even in a dry season like the long rains of 1992 (222 mm) there was apparently no competition for water from the hedgerows. Next, the runoff and soil loss modules were calibrated for all four seasons (short rains of 1991 through the long rains of 1993). Runoff plots planted with hedgerows of cassia (*Cassia siamea*, Lam.), as well as the mono-cropped plots were planted respectively with maize for two consecutive seasons, then cowpea (*Vigna unguiculata*, cv. K 80), and then maize again.

10.2.2 Application examples of SHIELD

After validation and calibration of SHIELD, the model was used to determine soil loss from a design storm. The hydrological concept of a design storm, which is a theoretical storm with a known depth, duration and recurrence interval, is often used to design soil and water conservation measures. The storm of 14 April 1990 (cf. Chapter 3) was selected because it generated the highest amount of soil loss in the measurement period, although storm depth

as well as erosivity were not the highest of that period. First, soil loss from mono-cropped maize in this storm was computed by using SHIELD. Subsequently, soil loss was computed if this storm would fall four weeks earlier (Julian day 76), two weeks earlier (Julian day 90), two weeks later (Julian day 118) or four weeks later (Julian day 132).

Land preparation has considerable influence on runoff and soil loss (Stroosnijder & Hoogmoed, 1984; Hoogmoed & Klaij, 1990). Depth and frequency of tillage operations are dynamic management practices that can be accurately described on a daily basis. First, the effect of a primary tillage before planting and its subsequent decline during the season is computed. The initial tillage depth ranges from zero tillage to 0.40 m depth. Average tillage depth of land preparation by hoeing in Machakos was 75 mm. A tillage depth of 0.1-0.2 m can be achieved by ox-drawn implements, and a further increase by tractor-drawn implements. The latter is a mechanical soil and water conservation technique called ridging or ridge and furrows. Additionally, the effect of secondary tillage, in this case mechanical weeding by hoeing, after 4, 6 or 8 weeks and tertiary tillage after 8 weeks following secondary tillage after 4 weeks on runoff and soil loss is computed.

SHIELD simulates the effect of mulch and hedgerows on runoff and soil loss and computes corresponding crop yields. The model was used to compute 20 consecutive seasons, from the short rains of 1983 through the long rains of 1993, with single- and double-row hedges, prunings applied as mulch or carried away, and with a hedgerow distance varying from 1-8 m. Application of the selected soil-loss tolerance values of 2 and 5 t ha⁻¹ y⁻¹ provides the corresponding optimum planting distance of hedgerow barriers.

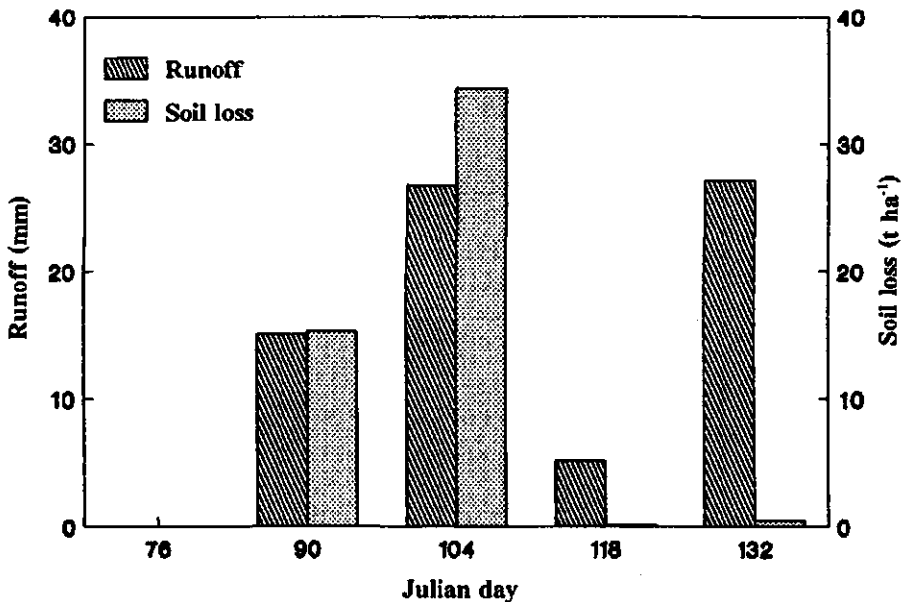


Fig. 10.1 SHIELD output: the effect of runoff and soil loss from a design storm that fell on Julian day 104, and the simulation of Julian dates 76, 90, 118 and 132.

10.3 Results

10.3.1 Design events

The storm that caused major soil loss on 14 April 1990 (Julian day 104) was selected as the design storm for this study. Soil loss from this storm was computed by using SHIELD at 34.3 t ha^{-1} , while the measured value was also 34.3 t ha^{-1} (cf. Chapter 3). The exact match between the measured and computed soil loss value is fortunate and not because SHIELD was calibrated for this season. It indicates, however, the accuracy of SHIELD despite the fact that it is a mechanistic model. There was a distinct difference in runoff and soil loss if the storm would fall on another date (Fig. 10.1). In the period soon after the start of the rainy season (Julian day 63) all excess rainfall is intercepted, due to a high surface storage after primary tillage and a relatively high moisture deficiency of the soil. Hence, there is no serious soil loss either. When the rainy season advances the amount of stored water in the soil increases. This phase is called the accumulation phase and it is followed by a depletion phase when the total stored water declines (cf. Chapter 5). Generally, it can be postulated that the further into the accumulation phase the higher the runoff amount, although intermediate tillage operations can temporarily increase the surface storage. Soil loss, on the other hand, can be considered as the product of runoff and sediment concentration. Runoff increases with the progress of the accumulation phase, but the corresponding value of sediment concentration depends on the vulnerability of the soil. The vulnerability depends on soil cover and on the incident amount of water in the soil, which is a function of rain that infiltrates in the two days preceding a storm (cf. Chapter 9). When the season progresses crop cover increases and so will the resistance to soil loss. However, the rain that has fallen on the two days preceding the storm is not tied to a specific date or water content phase, which makes the vulnerability of the soil variable and difficult to forecast. On Julian day 90, the preceding rainfall was 1.9 mm and on Julian days 118 and 132 it was also an insignificant amount. Tillage operations on Julian day 117 increased the surface storage, so that runoff on Julian day 118 was low. If the tillage operation was carried out later than Julian day 118 runoff would have been much higher, but soil loss would still be negligible.

10.3.2 Effect of depth and frequency of tillage on runoff and soil loss

The effect of tillage depth before planting in a mono-cropped maize field on runoff and soil loss is substantial. When the land is not tilled (NT) the average annual runoff is computed at 43.0 mm, while soil loss is 42.5 t ha^{-1} for 20 consecutive cropping seasons (Fig. 10.2). When the furrow depth increases to 0.23 m runoff is expected to decrease to 7.8 mm and soil loss to 5.7 t ha^{-1} . The effect of deeper tillage does not show a further substantial decrease. The effect of secondary tillage operations (ST) is small compared to primary tillage (PT), varying from an additional reduction of 10-20% at 4 weeks, 2-13% at 6 weeks, 1-3% at 8 weeks, on soil loss and runoff respectively (Fig. 10.3). The effect of a tertiary tillage operation (TT) is negligible compared to secondary tillage, a further reduction of 0-1% of runoff and soil loss from the field after the tillage operation at 4 weeks. The timing of a secondary tillage operation is decided on the presence and abundance of weeds. In Machakos it is usually 6 weeks after planting, which means that more than twice of the excess rainfall will be trapped in surface depressions (Fig. 10.4).

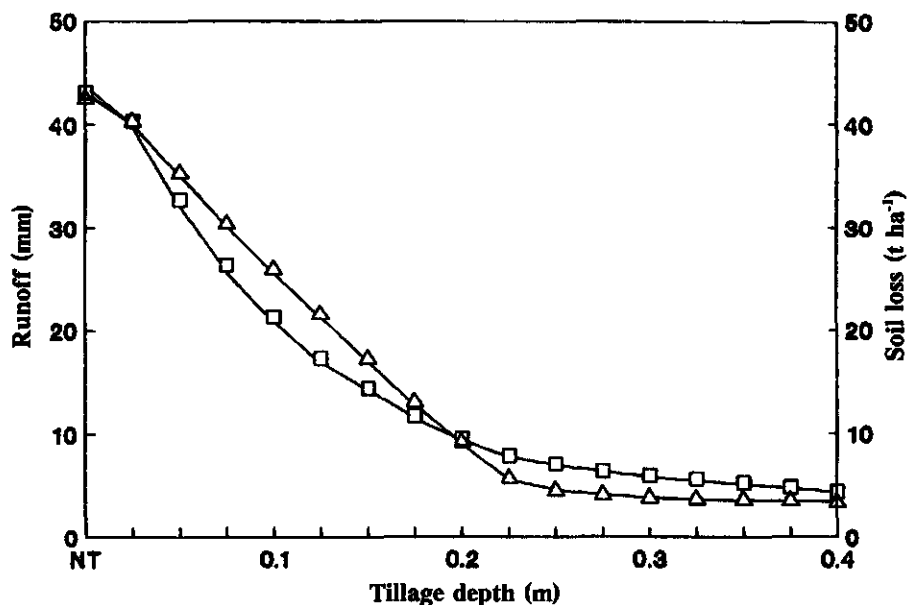


Fig. 10.2 SHIELD output: the effect of tillage depth (m) before planting on runoff (\square) and soil loss (Δ) from mono-cropped maize (20-season average).

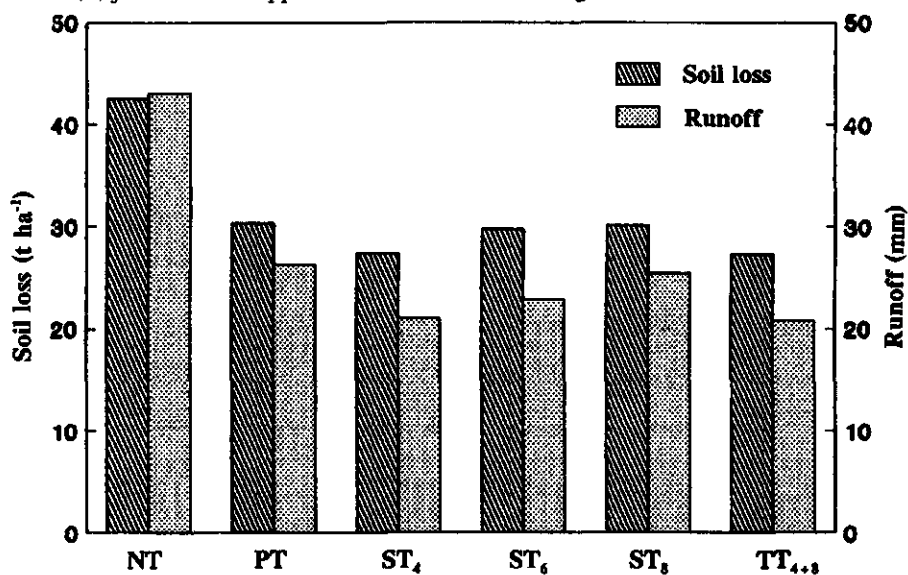


Fig. 10.3 SHIELD output: the effect of tillage frequency (75 mm depth) on runoff and soil loss. No-till (NT), primary tillage before planting (PT), secondary tillage after 4 (ST₄), 6 (ST₆) and 8 (ST₈) weeks and tertiary tillage (TT_{4,8}) after 4 and 8 weeks. (20-season average).

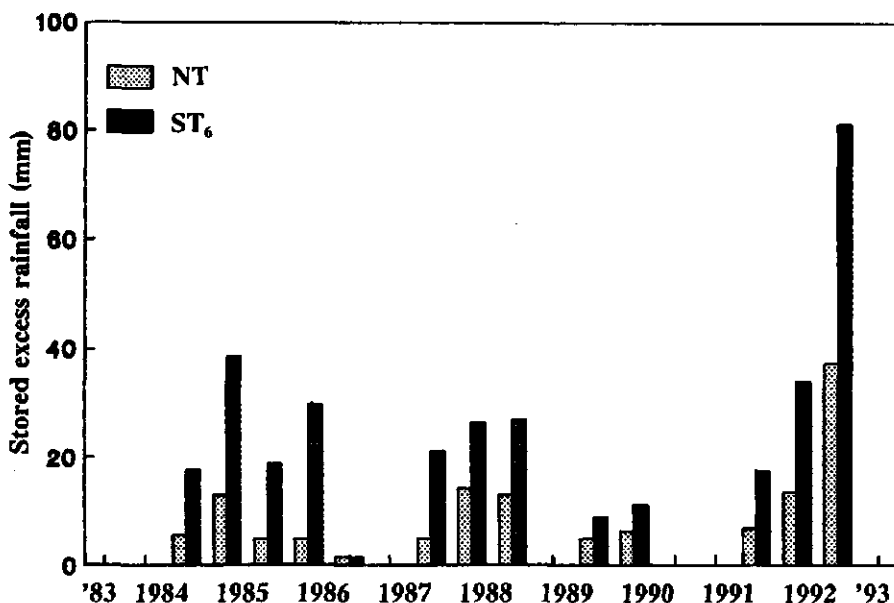


Fig. 10.4 SHIELD output: intercepted excess rainfall when no tillage (NT) or the normally-practised tillage operations (ST₆) have been applied.

10.3.3 Effect of hedgerows and mulch on runoff and soil loss

SHIELD was used to test the effect of hedgerows and mulch on runoff and soil loss for 20 consecutive cropping seasons. Well-fertilized maize was grown each season and the initial water content of the soil at the start of the growing season could be estimated from rainfall records of the previous season. Average annual runoff from the maize plot without erosion protection was computed to be 22.9 mm, while corresponding soil loss was 29.7 t ha⁻¹ and seasonal maize yield 2.05 t ha⁻¹. The effect of hedgerow spacing of single-row and double-row hedges was computed, both with and without mulch. The mulch application factor in SHIELD allows the user to take all or part of the tree prunings away for fodder consumption, while runoff, soil loss and crop yields can be computed with the remainder of tree prunings applied as mulch. If 5 t ha⁻¹ y⁻¹ is taken as tolerable soil loss limit single-row hedges should be planted 6 m apart and double-row hedges 8 m apart (Fig. 10.5). If 2 t ha⁻¹ y⁻¹ is taken as soil loss limit single-row hedges without mulch should be planted 2 m apart, but with mulch the distance can be extended to 5 m. Double-row hedges can be planted 3 m apart without mulch, with mulch to 7 m. It seems impossible to bring soil loss rates down to 0.1 t ha⁻¹ y⁻¹ or less. Planting distance of hedgerows, with or without mulch, had on average no effect on crop yields. However, when separate seasons were examined a distinction could be made between relatively wet (247-808 mm) and relatively dry (60-537 mm) seasons (Fig. 10.6). The respective crop yield decrease or increase with increasing hedgerow distance appeared to be closer related to rainfall distribution than total amount of rainfall.

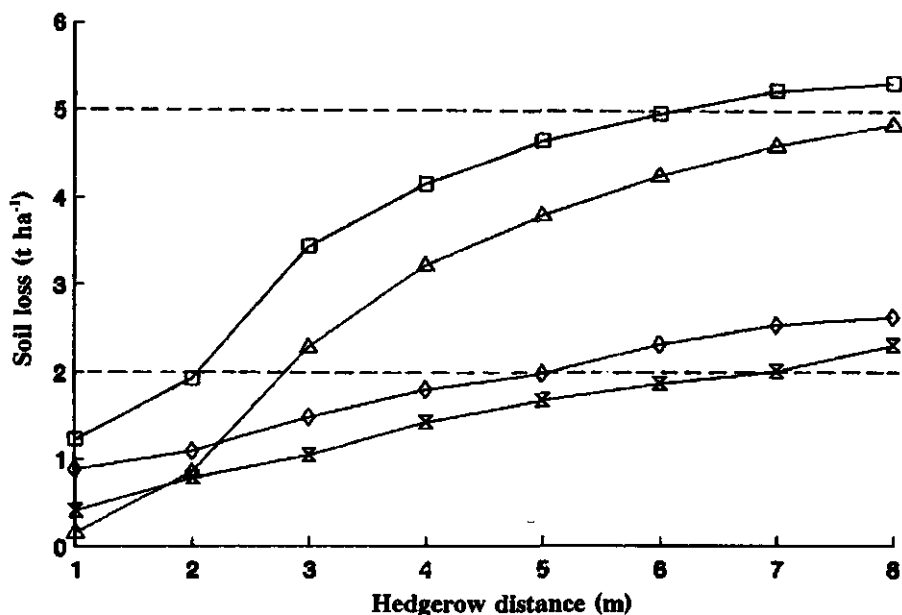


Fig. 10.5 SHIELD output: the effect of the distance (m) between single-row hedges with mulch applied (◇) and without mulch (□), and double-row hedges with mulch (X) and without mulch (Δ) on soil loss ($t\ ha^{-1}$, 20-season average).

10.4 Discussion

Generally, it can be stated that runoff increases with the proceeding of the accumulation phase. Soil loss, which is dependent on runoff as transporting agent, has, therefore, a chance to increase towards the end of the accumulation phase. However, soil loss is also dependent on the vulnerability of the soil to erosion, which is highly variable. The maximum amount of soil loss will always occur when detachment and transport capacities are balanced (Ellison, 1947a). The hydrological concept of design storm (section 10.2.2) does not represent a reliable design criterion for soil and water conservation measures. The major difficulty encountered with the design storm concept is that the effect of a rainstorm on soil and water conservation measures is time dependent. Clearly, the effect of the storm on the soil was due to the concurrence of circumstances and only partly due the recurrence of the design storm. It was shown by the simulation that the amount of runoff and soil loss depended strongly on the condition of the soil. It is better to use simulation modelling and generate a design event, rather than using a design storm, taking the condition of the soil into account at the moment of the storm. Incorrect conclusions about the suitability of conservation measures to withstand a design storm at one particular moment, but not at another moment, will be avoided.

Primary tillage operations by hoeing may reduce soil loss and runoff to 61-71% respectively. With the aid of tractor-drawn implements a created tillage depth of 0.2 m may reduce runoff

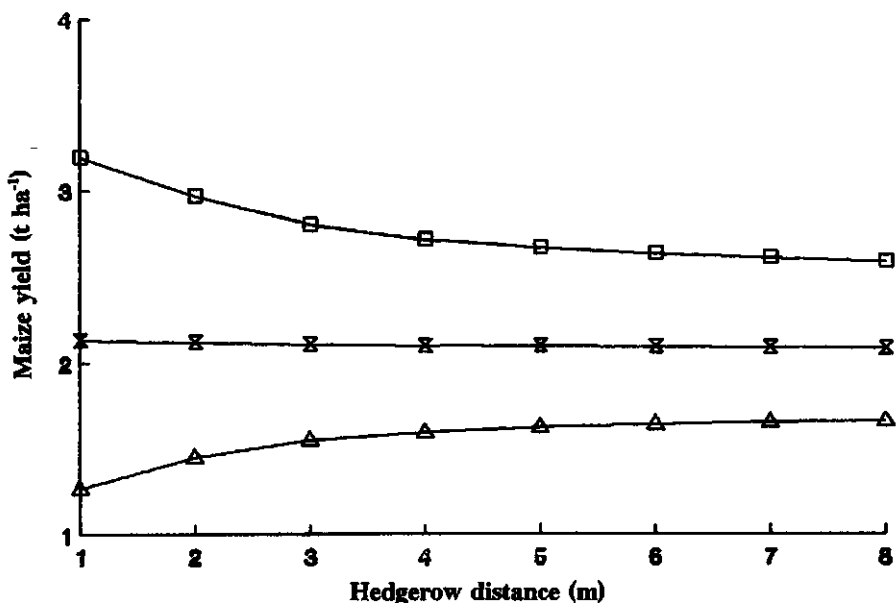


Fig. 10.6 SHIELD output: the effect of the distance (m) between single-row hedges in relatively wet seasons (□), relatively dry seasons (Δ) and the 20-season average (×) on seasonal maize yield (t ha⁻¹).

and soil loss to 22%. However, this ridge and furrow technique is usually practised in areas where there is little rain. Large storms can overtop the ridges, which poses a potential erosion hazard (Hudson, 1992). Water stored in surface depressions can be drained later in the storm by rill erosion, causing an unwanted increase in runoff (Ellison, 1947c). The effect of secondary tillage operation on a further reduction is smaller than primary tillage, varying from 10-20% at 4 weeks to 1-3% at 8 weeks. The timing of a secondary tillage operation is usually decided on the abundance of weeds growing. However, with regard to erosion control is more effective to weed after 4 weeks than after 6 weeks, so that the surface storage is increased with still some big storms to be expected. A rainy season in Machakos usually lasts 6-8 weeks, hence a tertiary tillage operation after 8 weeks is futile and a waste of resources.

With respect to runoff, the amount of water lost as plant available water is not as important as it is as transport agent of soil particles. An average annual water loss of 22.9 mm on unprotected slopes represents merely 3% of the annual rainfall. The average annual soil loss of 29.7 t ha⁻¹ is far too high to meet soil loss criteria and, therefore, the selection of annual soil loss as a design criterion appears correct. In hedgerow barrier systems runoff and soil loss increase at greater hedgerow distance. When tree prunings are taken away soil loss increased 5-8 times when the hedgerow distance increased from 1 to 8 m. The distance should be limited to 6 and 8 m for single and double-row hedges respectively to limit soil loss to 5 t ha⁻¹ y⁻¹, but the latter layout takes 50% more trees as investment. To meet the requirements for the lower soil loss limit of 2 t ha⁻¹ y⁻¹ mulch need to be cast on the alley to

keep the hedgerow distance at 5-7 m. Without mulch hedgerows need to be planted 2-3 m apart, which seems very close. However, positive results of planting hedgerows only 1 m apart on steep slopes (45%) were reported from Malawi (Banda et al., 1994). Planting double-row hedges mean on one hand an increase in planting distance, but on the other hand an additional investment of 33-43% more trees. More rigorous soil loss criteria, such as a tolerable soil loss of less than $0.1 \text{ t ha}^{-1} \text{ y}^{-1}$, seems virtually impossible to combine with crop production.

10.5 Conclusions and future research

SHIELD predicted runoff, soil loss and crop yield satisfactorily. With soil loss criteria as boundary conditions SHIELD can be used to compute the maximum hedgerow distance allowed on slopes to keep losses within acceptable limits. SHIELD fulfils the requirements as a tool to analyze the erosion process and can expose scientific lacunas to set the research agenda. As application tool for a wider audience more field tests need to be undertaken, particularly on a range of slope angles and in different agro-ecological zones. Further development of SHIELD should also include additional crop and hedgerow species. Simulation models of selected staple food crops are presently available, like wheat (Van Laar et al., 1992), millet (Jansen & Gosseye, 1986), rice (Wopereis et al., 1993), and a range of various annual crops (Penning de Vries et al., 1989). Recently, a register appeared containing 85 agro-ecosystem models (Plentinger & Penning de Vries, 1995). It should not be to big an effort to get other models incorporated as a module or linked to SHIELD, like e.g. the program DUET91 that combines three existing models (Stroosnijder et al., 1994).

A bigger effort will be to incorporate other hedgerow species, especially competitive ones. Competition is a process that is tentatively incorporated in SHIELD to simulate water uptake from crop and hedgerow, but used to a limited extend due to a lack of detailed knowledge. To develop the competition module further would certainly increase the applicability of SHIELD. Ideally, the next version of SHIELD should be able to predict a balance between a minimum of competition and a maximum of soil conservation. However, to achieve this stage more information is needed on plant interference and the exact location/compartments where crop and tree roots take water and nutrients from. Another important item that can extend the applicability of the model is the nutrient balance. The incorporation of a nutrient balance requires that the crop growth module needs to be extended to Production Level 3 (nitrogen and phosphorus balances), while the model presently assumes an amply fertilized crop (Production Level 2). This is specifically important because loss of plant nutrients in sediments and the selective removal of nutrients, the so-called nutrient enrichment ratio, are a major factor in nutrient depletion of agricultural land. Presently, the amply fertilized version of SHIELD conceals an envisioned yield decline, while nutrient depletion is a major threat to sustainable land use. Although SHIELD fulfils the goals that were originally set for this study, an extended version would provide an even better tool to analyze the soil and water conservation ability of hedgerow barriers and would serve mankind to fight the fast increasing problem of land degradation, which is a presently one of the most important threats to a sufficient food supply in the world.

References

- Adams, J.E., 1966. Influence of mulches on runoff, erosion, and soil moisture depletion. *Soil Sci. Soc. Am. Proc.*, 30: 110-114
- Agassi, M. and Ben-Hur, M., 1991. Effect of slope length, aspect and phosphogypsum on runoff and erosion from steep slopes. *Aust. J. Soil Res.*, 29: 197-207.
- Agustin, E.O. and Nortcliff, S., 1994. Agroforestry practices to control runoff and erosion on steeplands in Ilocos Norte, Philippines. In: J.K. Syers and D.L. Rimmer (eds.), *Soil science and sustainable land management in the tropics*. CAB International, Wallingford, 59-72.
- Ahn, P., 1977. Erosion hazard in farming systems in East Africa. In: D.J. Greenland and R. Lal (eds.), *Soil conservation and management in the humid tropics*. Wiley, Chichester, 165-176.
- Ahnert, F., 1982. Untersuchungen über das Morphoklima und die Morphologie des Inselberggebietes von Machakos, Kenia. In: F. Ahnert, H. Rohdenburg und A. Semmel. *Beiträgen zur Geomorphologie der Tropen (Ostafrika, Brasilien, Zentral- und Westafrika)*, Catena Supplement 2. Catena Verlag, Cremlingen, Germany, 1-72.
- Aina, P.O., Lal, R. and Taylor, G.S., 1977. Soil and crop management in relation to soil erosion in the rainforest of western Nigeria. In: G.R. Foster (ed.), *Soil erosion: prediction and control*. Soil Conserv. Soc. Am., Ankeny, Iowa, 75-82.
- Banda, A.Z., Maghembe, J.A., Ngugi, D.N. and Chome, V.A., 1994. Effect of intercropping maize and closely spaced *Leucaena* hedgerows on soil conservation and maize yields on a steep slope at Ntchue, Malawi. *Agrofor. Syst.*, 27: 17-22.
- Barber, R.G., Moore, T.R. and Thomas, D.B., 1979. The erodibility of two soils from Kenya. *J. Soil Sci.*, 30: 579-591.
- Batie, S.S., 1983. Soil erosion. The Conservation Foundation, Washington, D.C., 136 pp.
- Bennett, J.P., 1974. Concept of mathematical modelling of sediment yield. *Water Resour. Res.*, 10(3): 485-492.
- Bouma, J., Belmans, C.F.M. and Dekker, L.W., 1982. Water infiltration and redistribution in a silt loam subsoil with vertical worm channels. *Soil Sci. Soc. Am. J.*, 46: 917-921.
- Bouyoucos, G.J. 1935. The clay ratio as a criterion of susceptibility of soils to erosion. *J. Am. Soc. Agron.*, 27: 738-741.
- Braun, H.M.H., 1977. The reliability of the rainy seasons in Machakos and Kitui Districts. Miscellaneous Paper No. M12, Kenya Soil Survey, National Agricultural Laboratories, Nairobi, 20 pp.
- Brewbaker, J.L., 1989. Nitrogen-fixing trees for fodder and browse in Africa. In: B.T. Kang and L. Reynolds (eds.), *Alley farming in the humid and subhumid tropics*. IDRC, Ottawa, 55-70.
- Bruce-Okine, E. and Lal, R., 1975. Erodibility as determined by raindrop technique. *Soil Sci.*, 119: 149-157.
- Brussaard, L., Hauser, S. and Tian, G., 1993. Soil faunal activity in relation to the sustainability of agricultural systems in the humid tropics. In: K. Mulongoy and R. Merckx (eds.), *Soil organic matter dynamics and sustainability of tropical agriculture*. IITA and K.U. Leuven, Wiley, Chichester, pp. 241-256.
- Cannell, M.G.R., 1989. Physiological basis of wood production: a review. *Scand. J. For. Res.* 4: 459-490.

- Cannell, M.G.R., 1991. Plant management in agroforestry. In: M.E. Avery, M.G.R. Cannell and C.K. Ong (eds.), *Biophysical research for Asian agroforestry*. Winrock Int., New Dehli, 59-72.
- Chow, V.T., 1964. *Handbook of applied hydrology*. McGraw-Hill, New York, 1418 pp.
- Coster, Ch., 1932. Wortelstudiën in the tropen I: de jeugdontwikkeling van het wortelstelsel van een zeventigtal boomen en groenbemesters. *Tectona*, 25: 828-872.
- Coster, Ch., 1938. Bovengrondse afstroming en erosie op Java. *Tectona*, 31: 613-728.
- De Wit, C.T., 1960. On competition. *Pudoc*, Wageningen, 82 pp.
- De Wit, C.T. and Penning de Vries, F.W.T., 1982. L'analyse des systèmes de production primaire. In: F.W.T. Penning de Vries and M.A. Djiteye (eds.), *La productivité des pâturages Sahéliens*. Agric. Res. Rep. 918, *Pudoc*, Wageningen, 20-27.
- De Wit, C.T. and Van Keulen, H., 1987. Modelling production of field crops and its requirements. *Geoderma*, 40: 253-265.
- Driessen, P.M., 1986. The water balance of the soil. In: H. Van Keulen and J. Wolf (eds.), *Modelling of agricultural production: weather, soils and crops*. *Pudoc*, Wageningen, 76-116.
- Driessen, P.M. and Dudal, R. (eds.), 1989. *Lecture notes on the geography, formation, properties and use of the major soils of the world*. WAU, Wageningen and K.U. Leuven, Wageningen, 296 pp.
- Dunne, T., Dietrich, W.E. and Brunengo, M.J., 1978. Recent and past erosion rates in semi-arid Kenya. *Z. Geomorph. N. F., Suppl. Bd.*, 29: 130-140.
- Ellison, W.D., 1944. Studies of raindrop erosion. *Agric. Eng.*, 25: 131-136, 181-182.
- Ellison, W.D., 1947a. Soil erosion studies - part I. *Agric. Eng.*, 28: 145-146.
- Ellison, W.D., 1947b. Soil erosion studies - part II, soil detachment hazard by raindrop splash. *Agric. Eng.*, 28: 197-201.
- Ellison, W.D., 1947c. Soil erosion studies - part III, some effects of soil erosion on infiltration and surface runoff. *Agric. Eng.*, 28: 245-248.
- Ellison, W.D. and Ellison, O.T., 1947. Soil erosion studies - part VII, soil transportation by surface flow. *Agric. Eng.*, 28: 442-444, 450.
- Elwell, H.A., 1981. A soil loss estimation model for Southern Africa. In: R.P.C. Morgan (ed.), *Soil conservation: problems and prospects*. Wiley, Chichester, 281-292.
- FAO, 1988. *FAO-Unesco soil map of the world, Revised legend*. *World Soil Resources Report 60*. FAO, Rome, 119 pp.
- Foster, G.R., Lombardi, F. and Moldenhauer, W.C., 1982. Evaluation of rainfall-runoff erosivity factors for individual storms. *Trans. Am. Soc. Agric. Eng.*, 25: 124-129.
- Fujisaka, S., 1989. A method for farmer-participatory research and technology transfer: upland soil conservation in the Philippines. *Expl Agric.*, 25: 423-433.
- Fujisaka, S., 1993. A case of farmer adaptation and adoption of contour hedgerows for soil conservation. *Expl Agric.*, 29: 97-105.
- Gachene, C.K.K., 1989. Nutrient losses in eroded soil material from some Kenyan soils. In: D.B. Thomas, E.K. Biamah, A.M. Kilewe, L. Lundgren and B.O. Mochoge (eds.), *Soil and water conservation in Kenya*. Dep. Agric. Eng., Un. Nairobi and SIDA, Nairobi, 34-37.
- Gardner, C.M.K., Gardner, K., Bell, J.P., Cooper, J.D., Dean, T.J., Gardner, N. and Hodnett, M.G., 1991. Soil water content. In: K.A. Smith and C.E. Mullins (eds.), *Soil analysis: physical methods*. Marcel Dekker, New York, 1-73.
- Goudriaan, J., 1993. Model, schaal en aggregatieniveau. Inaugurele rede uitgesproken op 30 september 1993, WAU, Wageningen, 29 pp.

- Goudriaan, J. and Van Laar H.H., 1994. Modelling potential crop growth processes. Current issues in production ecology, vol. 2. Kluwer Academic Publishers, Dordrecht, 238 pp.
- Gregory, J.M., 1982. Soil cover prediction with various amounts and types of crop residue. Trans. Am. Soc. Agric. Eng., 25: 1333-1337.
- Hauser, S., 1993. Root distribution of *Dactyladenis (Acioa) barteri* and *Senna (Cassia) siamea* in alley cropping on Ultisol I: implication for field experimentation. Agrofor. Syst., 24: 111-121.
- Hoogmoed, W.B. and Klaij, M.C., 1990. Soil management for crop production in the West African Sahel. I: soil and climate parameters. Soil Tillage Res., 16: 85-103.
- Hudson, N., 1986. Soil conservation. Revised reprint. Batsford, London, 324 pp.
- Hudson, N.W., 1992. Land Husbandry. Batsford, London, 192 pp.
- Huxley, P.A., 1985. The tree/crop interface - or simplifying the biological/environmental study of mixed cropping agroforestry systems. Agrofor. Syst., 3: 251-266.
- Jabbar, M.A., Larbi, A. and Reynolds, L., 1994. Profitability of alley farming with and without fallow in Southwest Nigeria. Expl Agric., 30: 319-327.
- Jansen, D.M., and Gosseye, P., 1986. Simulation of growth of millet (*Pennisetum americanum*) as influenced by water stress. Simulation Reports CABO-TT, 10. CABO and Dept. Theor. Prod. Ecol., WAU, Wageningen, 108 p.
- Kamphorst, A., 1987. A small rainfall simulator for the determination of soil erodibility. Neth. J. Agric. Sci., 35: 407-415.
- Kang, B.T., Wilson, G.F. and Sipkens, L., 1981. Alley cropping maize (*Zea mays* L.) and leucaena (*Leucaena leucocephala* Lam.) in southern Nigeria. Plant Soil, 63: 165-179.
- Kerkhoven, A.R.W., 1913. Het tegengaan van afspoelingen door rationeele tuinaanleg. Soekaboemische Landbouw Vereeniging, Soekaboemi, Indonesia, 21 pp.
- Kibe, J.M., Ochung', H. and Macharia, P.N., 1981. Soils and vegetation of the ICRAF experimental farm (Machakos district). Detailed Soil Survey Report No. D23. Kenya Soil Survey, National Agricultural Laboratories, Nairobi, 68 pp.
- Kiepe, P., 1995. Effect of *Cassia siamea* hedgerow barriers on soil physical properties. Geoderma, 66: 113-120.
- Kiepe, P. and Rao, M.R., 1994. Management of agroforestry for the conservation and utilisation of land and water resources. Outlook Agric., 23: 17-25.
- Kiepe, P. and Young, A., 1992. Soil conservation through agroforestry: experience from four years of demonstrations at Machakos, Kenya. In: H. Hurni and K. Tato (eds.), Erosion, conservation and small-scale farming. Geographica Bernensia, Berne, 303-312.
- Kirkby, M.J., 1980. The problem. In: M.J. Kirkby and R.P.C. Morgan (eds.), Soil erosion. Wiley, Chichester, 1-16.
- König, D., 1991. Contributions des méthodes agro-forestières à la lutte anti-érosive au Rwanda. In: E. Roose (ed.), Réseau erosion. Bulletin 11. Montpellier, France, 185-191.
- Kozlowski, T.T., Kramer, P. and Pallardy, S.G., 1991. The physical ecology of woody plants. Academic Press, San Diego, 657 pp.
- Kuchelmeister, G., 1989. Hedges for resource-poor land users in developing countries. GTZ, Eschborn, Germany, 256 pp.
- Laflen, J.M., Elliot, W.J., Simanton, J.R., Holzhey, C.S. and Kohl, K.D., 1991. WEPP: soil erodibility experiments for rangeland and cropland soils. J. Soil Water Conserv., 46: 39-44.
- Laflen, J.M., Lal, R. and El-Swaify, S.A., 1990. Soil erosion and sustainable agriculture. In: C.A. Edwards, R. Lal, P. Madden, R.H. Miller and G. House (eds.), Sustainable agricultural systems. Soil Water Cons. Soc., Ankeny, Iowa, 569-581.

- Lal, R., 1988. Soil erosion control with alley cropping. In: Sanam Rimwanich (ed.), Land conservation for future generations. Proceedings of the 5th Int. Soil Cons. Conf., Vol.1., Dep. of Land Development, Bangkok, 237-245.
- Lal, R., 1989. Agroforestry systems and soil surface management of a tropical alfisol: V. Water infiltrability, transmissivity and soil water sorptivity. *Agrofor. Syst.*, 8: 217-238.
- Linden, D.R. and Dixon, R.M., 1976. Soil air pressure effects on rate and rate of infiltration. *Soil Sci. Soc. Am. J.*, 40: 963-965.
- List, R.J., 1968. Smithsonian meteorological tables. Sixth revised edition. Smithsonian Institute, Washington D.C., 527 pp.
- Lundgren, B. and Nair, P.K.R., 1985. Agroforestry for soil conservation. In: S.A. El-Swaify, W.C. Moldenhauer and A. Lo (eds.), Soil erosion and conservation. Soil Water Conserv. Soc., Ankeny, Iowa, 703-717.
- Metzner, J.K., 1976. Lamtoronisasi: an experiment in soil conservation. *Bull. Indonesian Econ. Studies*, 12: 103-109
- Meyer, L.D. and Wischmeier, W.H., 1969. Mathematical simulation of the process of soil erosion by water. *Trans. Am. Soc. Agric. Eng.*, 12(6): 754-758, 762.
- Monteith, J.L. and Unsworth, M.H., 1990. Principles of environmental physics. Second edition. Edward Arnold, London, 291 pp.
- Morgan, R.P.C., 1986. Soil erosion and conservation. Longman, Harlow, UK, 298 pp.
- National Academy of Sciences, 1980. Firewood crops: shrub and tree species for energy production. National Academy Press, Washington D.C., 228 pp.
- Ong, C.K. and Khan, A.A.H., 1993. The direct measurement of water uptake by individual tree roots. *Agrofor. Today* 5(4): 2-5.
- Ong, C.K., Corlett, J.E., Singh, R.P. and Black, C.R., 1991. Above- and below-ground interactions in agroforestry systems. *For. Ecol. Manage.*, 45: 45-59.
- Palm, C.A. and Sanchez, P.A., 1991. Nitrogen release from the leaves of some tropical legumes as affected by their lignin and polyphenolic contents. *Soil Biol. Biochem.*, 23: 83-88.
- Panigbatan, E.P., 1990. Alley cropping for managing soil erosion in sloping lands. *Trans. 14th Int. Cong. Soil Sci.*, 7. Int. Soil Sci. Soc., Kyoto, Japan, 376-377.
- Parlevliet, J.E., 1993. Meer en beter met minder. Voordracht bij het afscheid als hoogleraar in de plantenveredeling aan de Landbouwniversiteit te Wageningen op 4 november 1993, WAU, Wageningen, 25 pp.
- Pearcy, R.W., Ehleringer, J., Mooney, H.A. and Rundel, P.W., 1989. Plant physiological ecology: field methods and instrumentation. Chapman and Hall, London, 457 pp.
- Pellek, R., 1992. Contour hedgerows and other soil conservation interventions for the hilly terrain of Haiti. In: K. Tato and H. Hurni (eds.), Soil conservation for survival. Soil Water Conserv. Soc., Ankeny, Iowa, 313-320.
- Penning de Vries, F.W.T., Jansen, D.M., Ten Berge, H.F.M. and Bakema, A. (eds.), 1989. Simulation of ecophysiological processes of growth in several annual crops. Simulation Monographs, 29. Pudoc, Wageningen, 271 pp.
- Peterson, A.E. and Bubenzer, G.D., 1986. Intake rate: sprinkler infiltrometer. In: A. Klute (ed.), Methods of soil analysis, part 1, physical and mineralogical methods. Agronomy Monograph 9 (2nd edition). Am. Soc. Agron., Madison, USA, 845-870.
- Peterson, J.B., 1964. The relation of soil fertility to erosion. *J. Soil Water Conserv.*, 19: 15-19.

- Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R. and Blair, R., 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science*, 267: 1117-1123.
- Plentinger, M.C. and Penning de Vries, F.W.T. (eds.), 1995. CAMASE, Register of agroecosystems models, version 1. AB-DLO, Wageningen, 179 pp.
- Rabbinge, R. and De Wit, C.T., 1989. Systems, models and simulation. In: R. Rabbinge, S.A. Ward and H.H. Van Laar (eds.), *Simulation and systems management in crop protection. Simulation Monographs 32*. Pudoc, Wageningen, 3-15.
- Rao, M.R., Ong, C.K., Pathak, P. and Sharma, M.M., 1991. Productivity of annual cropping and agroforestry systems on a shallow Alfisol in semi-arid India. *Agrofor. Syst.*, 15: 51-63.
- Reeves, M. and Miller, E.E., 1975. Estimating infiltration for erratic rainfall. *Water Resour. Res.*, 11 :102-110.
- Reynolds, L. and Atta-Krah, A.N., 1989. Alley farming with livestock. In: B.T. Kang and L. Reynolds (eds.), *Alley farming in the humid and subhumid tropics*. IDRC, Ottawa, 27-36.
- Rose, C.W., 1993. Erosion and sedimentation. In: M. Bonell, M.M. Hufschmidt and J.S. Gladwell (eds.), *Hydrology and water management in the humid tropics: hydrological research issues and strategies for water management*. Unesco and Cambridge University Press, 301-343.
- Rose, C.W., Parlange, J.Y., Sander, G.C., Campbell, S.Y. and Barry, D.A., 1983. Kinematic flow approximation to runoff on a plane: an approximate analytic solution. *J. Hydrol.*, 62: 363-369.
- Schmidt, J., 1992. Modelling long-term soil loss and landform change. In: A.J. Parsons and A.D. Abrahams, (eds.), *Overland flow*. U.C.L.-Press, London, 409-433.
- Schuitmaker, B., 1949. Maatregelen tot het behoud van de bodem in het inheemse landbouwbedrijf op Java. *Landbouw (Buitenzorg)*, 21: 153-176
- Singh, R.P., Van den Beldt, R.J., Hocking, D. and Korwar, G.R., 1989. Alley farming in the semi-arid regions of India. In: B.T. Kang and L. Reynolds (eds.), *Alley farming in the humid and subhumid tropics*. IDRC, Ottawa, 108-122.
- Soil Survey Staff, 1990. Keys to soil taxonomy. S.M.S.S. Technical Monograph 19, fourth edition. Virginia Polytechnic and State University, Blacksburg, Virginia, 422 pp.
- Stocking, M. and Elwell, H., 1976. Vegetation and erosion: a review. *Scottish Geographical Magazine*, 92: 4-16.
- Stroosnijder, L., 1976. Infiltratie en herverdeling van water in grond. Versl. Landbouwk. Onderz., 847. Pudoc, Wageningen, 213 pp.
- Stroosnijder, L., 1982. Simulation of the soil water balance. In: F.W.T. Penning de Vries and H.H. van Laar (eds.), *Simulation of plant growth and crop production. Simulation Monographs*, Pudoc, Wageningen, 175-193.
- Stroosnijder, L., 1989a. Maize growth in a tropical environment, part I: potential production. Dept. Irr. and Soil Water Conserv., WAU, Nieuwe Kanaal 11, 6709 PA Wageningen, 48 pp.
- Stroosnijder, L., 1989b. Maize growth in a tropical environment, part II: rainfed production. Dept. Irr. and Soil Water Conserv., WAU, Nieuwe Kanaal 11, 6709 PA Wageningen, 65 pp.
- Stroosnijder, L. and Hoogmoed, W.B., 1984. Crust formation on sandy soils in the Sahel II: tillage and its effects on the water balance. *Soil Tillage Res.*, 4: 321-337.

- Stroosnijder, L., Hoogmoed, W.B. and Berkhout, J.A.A., 1994. Modelling effects of water conservation tillage in the semi-arid tropics. In: J. Libbey (ed.), *Bilan hydrique agricole et sécheresse en Afrique tropicale*, Eurotext, Paris, 235-251.
- Stroosnijder, L. and Koorevaar, P., 1972. Air-pressure within soil-aggregates during quick wetting and subsequent 'explosion'. *Meded. Rijksfac. Landbouwwet. Gent* 37 (3): 1095-1106.
- Tacio, H.D., 1993. Sloping Agricultural Land Technology (SALT): a sustainable agroforestry scheme for the uplands. *Agrofor. Syst.*, 22: 145-152
- Thornton, P.K., Dent, J.B. and Caldwell, R.M., 1990. Applications and issues in the modelling of intercropping systems in the tropics. *Agric. Ecosystems Environ.*, 31: 133-146.
- Troeh, F.R. and Thompson, L.M., 1993. *Soils and soil fertility*. Fifth edition. Oxford Univ. Press, New York, 462 pp.
- Van Eijk-Bos, C. and Moreno, L.A., 1986. Barreras vivas de *Gliricidia sepium* (Jacq.) Steud. (matarratón) y su efecto sobre la pérdida de suelo en terrenos de colinas bajas-Urabá (Colombia). *Conif Informa No. 6*. CONIF, Bogotá, Colombia, 16 pp.
- Van Keulen, H. and Van Beek, C.G.E.M., 1971. Water movement in layered soils: a simulation model. *Neth. J. Agric. Sci.*, 19: 138-153.
- Van Keulen, H., Goudriaan, J., Stroosnijder, L., Lantinga, E.A. and Van Laar, H.H., 1992. Crop growth model for water-limited conditions (SUCROS2). In: Van Laar, H.H., Goudriaan, J. and Van Keulen, H. (eds.), *Simulation of crop growth for potential and water-limited production situations (as applied to spring wheat)*. Simulation Reports CABO-TT 27, CABO-DLO, Wageningen, 27-72.
- Van Kraalingen, D.W.G., Rappoldt, C. and Van Laar, H.H., 1994. The FORTRAN Simulation Translator (FST), a simulation language. In: J. Goudriaan and H.H. van Laar. *Modelling potential crop growth processes*. Kluwer Academic Publishers, Dordrecht, 219-230.
- Van Laar, H.H., Goudriaan, J. and Van Keulen, H. (eds.), 1992. *Simulation of crop growth for potential and water-limited production situations (as applied to spring wheat)*. Simulation Reports CABO-TT 27, CABO-DLO, Wageningen, 72 pp.
- Van Noordwijk, M., Hairiah, K., Seykhfani, M.S. and Flach, E.N., 1991a. *Pelthophorum pterocarpa* (DC.) Back (Caecalpiniaceae), a tree with a root distribution suitable for alley cropping in the humid tropics. In: B.L. McMichael and H. Persson (eds.), *Plant roots and their environment*. Elsevier, Amsterdam, 526-532.
- Van Noordwijk, M., Widiyanto, Heinen, M. and Hairiah, K., 1991b. Old tree root channels in acid soils in the humid tropics: important for root penetration, water infiltration and nitrogen management. *Plant Soil*, 134: 37-44.
- Wiersum, K.F., 1984. Surface erosion under various tropical agroforestry systems. In: C.L. O'Loughlin and A.J. Pearce (eds.), *Symposium on effects of forest land use on erosion and slope stability*. East-West Center, Honolulu, Hawaii, 231-239.
- Wiersum, K.F., 1985. Effects of various vegetation layers in an *Acacia auriculiformis* plantation on surface erosion in Java, Indonesia. In: S.A. El-Swaify, W.C. Moldenhauer and A. Lo (eds.), *Soil erosion and conservation*. Soil Cons. Soc. Am., Ankeny, 79-88.
- Wiersum, K.F., 1994. Farmer adoption of contour hedgerow intercropping, a case study from Indonesia. *Agrofor. Syst.*, 27: 163-182.
- Willey, R.W., 1979. Intercropping - its importance and research needs I: competition and yield advantages. *Field Crops Abstract*, 32: 1-10.

- Williams, J., Ross, P.J. and Bristow, K.L., 1991. Perspicacity, precision and pragmatism in modelling crop water supply. In: R.C. Muchow and J.A. Bellamy (eds.), *Climatic risk in crop production: models and management for the semiarid tropics and subtropics*. C.A.B. International, Wallingford, 73-96.
- Williams, J.R., Jones, C.A. and Dyke, P.T., 1984. A modelling approach to determining the relationships between erosion and soil productivity. *Trans. Am. Soc. Agric. Eng.*, 27: 129-144.
- Wischmeier, W.H., 1960. Cropping-management factor evaluations for a universal soil-loss equation. *Soil Sci. Soc. Am. Proc.*, 23: 322-326.
- Wischmeier, W.H., 1962. Storms and soil conservation. *J. Soil Water Cons.*, 17: 55-59.
- Wischmeier, W.H. and Mannering, J.V., 1965. Effect of organic matter content of the soil on infiltration. *J. Soil Water Cons.*, 20: 150-152.
- Wischmeier, W.H. and Mannering, J.V., 1969. Relation of soil properties to its erodibility. *Soil Sci. Soc. Am. Proc.*, 33: 131-137.
- Wischmeier, W.H. and Smith, D.D., 1978. Predicting rainfall erosion losses, a guide to conservation planning. *Agric. Handb. No. 537*, U.S.D.A., Washington D.C., 58 pp.
- Wood, P.J. and Burley, J. 1991. A tree for all reasons, introduction and evaluation of multipurpose trees for agroforestry. ICRAF, Nairobi, 158 pp.
- Wopereis, M.C.S., Kropff, M.J., Hunt, E.D., Sanidad, W. and Bouma, J. 1993. Case study on regional application of crop growth simulation models to predict rainfed rice yields, Tarlac Province, Philippines. In: B.A.M. Bouman, H.H. Van Laar and Wang Zhaoqian (eds.), *Agro-ecology of rice-based cropping systems*, SARP Research Proceedings, CABO-DLO, Wageningen, 27-46.
- Yamoah, C.F., Agboola, A.A., Wilson, G.F. and Mulongoy, K., 1986. Soil properties as affected by the use of leguminous shrubs for alley cropping with maize. *Agric. Ecosystems Environ.*, 18: 167-177.
- Young, A., 1986. Evaluation of agroforestry potential in sloping areas. In: W. Siderius (ed.), *Land evaluation for land-use planning and conservation in sloping areas*. ILRI Publication 40, ILRI, Wageningen, 106-132.
- Young, A., 1988. Agroforestry and its potential to contribute to land development in the tropics. *J. Biogeography*, 15: 19-30.
- Young, A., 1989. Agroforestry for soil conservation. C.A.B. International and ICRAF, Wallingford, 276 pp.
- Young, A., 1993. Agroforestry as a viable alternative for soil conservation. *Entwicklung und Landlicher Raum*, 27: 3-7.
- Young, R.A. and Mutchler, C.K., 1969. Soil movement on irregular slopes. *Water Resour. Res.*, 5: 1084-1089.

Summary

Water erosion is an environmental time bomb. In the last 45 years about 18 percent of the agricultural land in the world has been abandoned because it suffered from water erosion. Moreover, due to a paucity of level land, steep slopes are increasingly being cultivated, which will only exacerbate the problem. Abandoning degraded lands and shifting to new land will become increasingly difficult as the limits of the land that can be taken into production will soon be reached. Suitable soil and water conservation measures are needed to increase the sustainability of farming on slopes. A cost effective method of soil and water conservation is planting hedgerow barriers against erosion. Hedgerow barriers control runoff and, therefore, soil loss, provide mulch or fodder and are cheaper to install than mechanical erosion barriers, such as banks or ditches. In order to evaluate the potential of hedgerow barriers, a study was undertaken to quantify the efficacy of hedgerow barriers for controlling erosion and to help disentangle the crucial processes involved in gaining more knowledge about the functioning of the system. When that is accomplished, better and more effective designs of hedgerow barrier systems can be realized. The study required a number of skilled workers and precious equipment, which forced the decision to undertake it on the ICRAF Research Station at Machakos, Kenya.

The tree species chosen for the study was cassia (*Cassia siamea*, syn. *Senna siamea*), because it fulfilled the necessary requirements. The selection of the most suitable tree species for an agroforestry system depends on the demands of the land user. In mixed farming the production of fodder is important, especially in the dry season in semi-arid areas. On soils that are prone to erosion, mulching can be an option, but plant biomass that possesses good mulch and fodder characteristics is seldom found in a single species. Besides, a high production of tree biomass in intercropping systems occurs at the expense of the crop, at least in areas where water, nutrients or both are limited. A careful selection of the most suitable species is, therefore, essential. A study comparing the effect of hedgerows and mulch in a hedgerow barrier system, where cassia was grown with maize (*Zea mays*, cv. Katumani composite B) and cowpea (*Vigna unguiculata*, cv. K 80) in sequence, showed that hedgerows were more effective than mulch in controlling runoff and soil loss. A combination of hedgerows and mulch provided the best result, because detachment as well as sediment transport is controlled. Crop yields in the hedgerow barrier plots were more or less equal in the study to the yield of the control plots, which showed that the hedgerows did not have an adverse effect on the crops.

The question of how runoff and soil loss were reduced in the hedgerow barrier trials can be answered when infiltration rates are studied. Infiltration rates were measured with a portable rainfall simulator along transects across alleys and hedgerows. It appeared that the infiltration rates beneath the hedgerows were 3-8 times higher than in the area where the crops were grown. The increase in infiltration was partly caused by the physical barrier effect of the tree stems and partly by an increase in macropores beneath the hedgerow, probably due to an increase in activity of soil fauna, soil organic matter content and old root channels. The saturated hydraulic conductivity of the topsoil beneath the hedgerow appeared to be twice as high as under the crop. There was no increase in hydraulic conductivity detected in the subsoil. However, neutron probe measurements demonstrated higher soil water contents in

the subsoil beneath hedgerows after rainstorm events, indicating that there must be some form of preferential flow to the subsoil. Accumulation of soil water in the rainy season was consistently greater beneath the hedgerow than beneath the crops. It was only at the end of the depletion phase that the amount of soil water beneath the hedgerow reached the same value as the amount beneath the crops. In the course of time, as the hedgerow matured, the soil of the tree-crop interface became increasingly involved in storing trapped runoff. It indicated that the efficacy of the system to control runoff increased over time.

Different infiltration and redistribution patterns were distinguished between the various components of the hedgerow barrier system, i.e. beneath the hedgerow and beneath the crop, the latter with or without mulch. Based on these experimental data, an analytical framework was developed that quantified infiltration, overland flow and soil loss. The impact of the implied components and a small number of proposed variables and parameters on overland flow and soil loss were quantified on a seasonal basis. Subsequently, the analytical framework that was developed to calculate the effect of single-row hedges was expanded to hedgerows containing multiple rows of trees. The conclusion was, however, that the impact of three or more tree rows in one hedge is negligible compared with the impact of double rows. Now that the impact of both single-row hedges with and without mulch had been quantified as well as the impact of multi-row hedges, the study was extended to quantify the effect of double-row hedges with mulch that were planted at two distances apart. The impact of double-row hedges was quantified with additional algorithms, using the same impact parameters. The analytical framework that was finally developed can be used to calculate the effect of hedgerows, containing any number of tree rows, with and without mulch and planted at any distance apart, on runoff and soil loss.

The result of seasonal runoff and soil loss values that was predicted using the framework was encouraging. Seasons without extreme events were predicted accurately, while seasons with extreme events were not, as expected. In semi-arid areas the bulk of soil loss caused by water erosion can be characterised by a few extreme events that happen once every so many years. The amount of soil being washed away is not only dependent on the erosive power of the rainstorm, but is also strongly dependent on the vulnerability of the soil to erosion. Hence, the amount of soil lost is not related to the recurrence interval of a design storm, but to the concurrence of certain circumstances, namely the occurrence of a major rainstorm and the occurrence of a vulnerable soil at that particular moment. In the study area, the vulnerability of the soil to erosion was closely correlated with the soil water content, a condition that changes from day to day. The most plausible option for calculating the vulnerability of the soil at the time that an erosive storm occurs is, therefore, dynamic simulation modelling. Moreover, simulation modelling can also compute the actual soil cover by mulch or plant canopy at the time of a rainstorm. Actual soil cover is another important dynamic factor that influences soil loss. A dynamic simulation model called SHIELD (Simulation of Hedgerow Intervention against Erosion and Land Degradation) was developed to compute the effect of hedgerow barriers and mulch on runoff, soil loss and crop yields. An already existing crop growth model called MAIZE2 was incorporated within SHIELD as a crop growth module. SHIELD uses daily time steps, but the time base of rainfall is converted to an event by limiting the amount of time by a so-called rainfall duration table. Infiltration and the redistribution of infiltrated water are also limited to the length of the event. The overland flow from the hedgerow barrier system is calculated first. The sediment concentration is then parametrically computed for each storm, which is subsequently used to

calculate soil loss. SHIELD allows the user to design the optimum lay-out of hedgerow distance and density, and decide whether to apply mulch or not, under user-defined boundary conditions. Care must be taken that SHIELD assumes Production Level 2, which means that water may be limited, but nutrients are not. A future expansion of SHIELD will be the inclusion of modules for a nutrient limited situation. It will then provide a more accurate model regarding plant production and the application range of the model will also be enhanced. A model like SHIELD, which is a tool for understanding the soil and water conservation ability of hedgerow barriers, is important for tackling land degradation, which is presently one of the most important threats to a sufficient food supply in the world.

Samenvatting

Watererosie is een ecologische tijdbom. Gedurende de afgelopen 45 jaar is in de wereld achttien procent van het gecultiveerde land verloren gegaan door watererosie. Door een nog steeds toenemende vraag naar bouwland en een gebrek aan vlak land worden steeds steilere hellingen in cultuur gebracht, hetgeen de situatie alleen maar verergert. Het verlaten van gedegradeerde gronden, gevolgd door het ingebruiknemen van nieuwe gebieden wordt steeds moeilijker, aangezien de grenzen aan de hoeveelheid voor landbouw beschikbaar land spoedig bereikt zullen zijn. Goede bodem- en waterconserveringsmaatregelen zijn nodig om de duurzaamheid van de bestaande landbouw op hellingen zoveel als mogelijk te waarborgen. Een veelbelovende manier van bodem- en waterconservering is de aanplant van heggen op hoogtelijnen. Deze zogenaamde anti-erosieheggen controleren afstromend water en helpen daarbij het verlies van grond te beperken, leveren mulch of veevoer en de aanleg van heggen is bovendien goedkoper dan het implanteren van cultuurtechnische maatregelen. Om het potentieel van deze anti-erosieheggen te evalueren werd een onderzoek ingesteld naar het effect dat deze heggen hebben op het verminderen van bovengrondse afstroming, door de cruciale processen die hierbij een rol spelen te bepalen. Op deze manier kan meer inzicht worden verkregen in het functioneren van het anti-erosiehegsysteem. Dat is nodig om in de toekomst betere en effectievere systemen te kunnen ontwerpen. Omdat het onderzoek veel mankracht vroeg en het gebruik van kostbare apparatuur vergt, werd het op het proefstation van ICRAF in Machakos (Kenia) uitgevoerd.

Het kiezen van de meest geschikte boomsoort voor een bepaald agroforestrystelsel is van cruciaal belang, maar wordt in de praktijk vooral bepaald door de wensen van de landgebruiker. Op een gemengd bedrijf is, bijvoorbeeld, de produktie van veevoer belangrijk, vooral in de droge tijd in semi-aride gebieden. Op erosiegevoelige gronden is mulching een geschikte manier om erosie te bestrijden. Helaas hebben boombladeren hetzij goede mulcheigenschappen hetzij een hoge voedingswaarde, maar zelden zijn beide eigenschappen verenigd in een soort. Bovendien gaat een hoge produktie van blad in een gemengde teelt ten koste van de gewasproduktie, in ieder geval in gebieden waar water en voedingsstoffen of een van beide beperkend zijn. Een nauwkeurige selectie van de meest geschikte boomsoort is dan ook van het grootste belang voor het slagen van de introductie van een agroforestrystelsel. De boomsoort die voor dit onderzoek werd geselecteerd was cassia (*Cassia siamea*, syn. *Senna siamea*). Ten eerste, vanwege de goede mulchkwaliteit en ten tweede vanwege de geringe concurrentie met het gewas. Het onderzoek naar het effect van heggen en mulch in anti-erosiehegsystemen, waar naast cassia, maïs (*Zea mays*, cv. Katumani composite B) en koeieboon (*Vigna unguiculata*, cv. K 80) werden geteeld in een gewasrotatie, toonde aan dat de heggen effectiever waren dan mulch in het verminderen van afstroming. Een combinatie van heggen en mulch gaf zoals verwacht het beste resultaat, omdat erosie door beide werd bestreden. De gewasopbrengst in de hegsystemen was ongeveer gelijk aan de opbrengst van de controle plots, zodat mag worden aangenomen dat deze heggen geen negatieve invloed op het gewas uitoefenden.

Om de vraag te beantwoorden in welke mate afstroming en grondverlies door heggen worden beperkt dient in de eerste plaats de infiltratie nader te worden beschouwd. Infiltratiesnelheden werden gemeten met behulp van een draagbare regenvalsimulator. De metingen werden

uitgevoerd langs transecten die dwars door de heggen liepen. De infiltratiesnelheid bleek onder een heg 3-8 maal hoger te zijn dan in de gebieden ernaast, waar het gewas stond. De toename in infiltratie onder de heg werd ten eerste veroorzaakt door de remmende werking die de stam op de afstroming uitoefende en ten tweede door een toename van macroporieën onder de heg. Dat laatste werd waarschijnlijk veroorzaakt door een toename van bodemfauna, organisch materiaal en oude wortelkanalen. De verzadigde doorlatendheid van de bovengrond onder de heg bleek twee maal zo hoog te zijn als onder het gewas. Er werd geen verschil ontdekt in de verzadigde doorlatendheid van de ondergrond. Metingen met een neutronen-sonde gaven echter aan dat het vochtgehalte onder de heg direct na een regenbui ook dieper in de ondergrond verder toenam dan in de grond onder het gewas, hetgeen wijst op een vorm van preferente stroming. Opeenhoping van bodemvocht was onder de heg steeds hoger dan onder het gewas gedurende het hele groeiseizoen. Slechts aan het eind van de water-onttrekkingsfase, op het moment dat het gewas bijna rijp was, daalde de totale voorraad bodemvocht onder de heg tot dezelfde waarde als onder het gewas. Na ieder seizoen, bij het ouder worden van de heg, werd het gebied dat meer water kon bevatten steeds uitgebreider, hetgeen duidde op het toenemen van de effectiviteit van de heggen in de loop der tijd.

De gemeten verschillen in infiltratie en vochtverdeling tussen de grond onder de heg en de grond onder het gewas, werden gebruikt voor de ontwikkeling van een analytisch kader om infiltratie, afstroming en grondverlies te kwantificeren. Het effect van heggen, die uit een enkele bomenrij bestonden, en mulch op afstroming en grondverlies werd met behulp van een beperkt aantal variabelen en parameters op seizoensbasis gekwantificeerd. Vervolgens werd dit analytisch kader uitgebreid met enkele formules die het effect op afstroming beschrijven van heggen, die meerdere bomenrijen bevatten. De conclusie was dat een dubbele bomenrij beter was dan een enkele, zij het niet twee maal beter, en dat het effect van drie of meer bomenrijen weinig toevoegde in vergelijking tot een dubbele bomenrij. Nadat het effect van zowel enkele-rij heggen met en zonder mulch en het effect van meerdere-rij heggen afzonderlijk gekwantificeerd was, werd het onderzoek uitgebreid naar dubbele-rij heggen met mulch. Het effect van dubbele-rij heggen werd gekwantificeerd met behulp van enkele nieuwe formules, die echter van dezelfde variabelen en parameters gebruik maakten. Het analytisch kader dat uiteindelijk ontwikkeld was kan het effect op afstroming en afspoeling berekenen van heggen, die uit een of meer bomenrijen bestaan en waar mulching al dan niet toegepast wordt.

De voorspellingen die gedaan werden op basis van het opgestelde analytische kader waren accuraat. Afstroming en grondverlies werden nauwkeurig voorspeld. Voor seizoenen met uitzonderlijk grote stortbuien daarentegen niet, hetgeen in de lijn der verwachting lag. In semi-aride gebieden kan het grootste gedeelte van het grondverlies worden toegeschreven aan incidenteel voorkomende stortbuien. De hoeveelheid grond die dan afspoelt is sterk afhankelijk van de erosiegevoeligheid van de grond naast de erosieve kracht van de stortbui. Grondverlies is derhalve niet alleen afhankelijk van het voorkomen van een uitzonderlijk grote stortbui, maar van een samenloop van omstandigheden: zowel van de komst van een uitzonderlijk grote stortbui als het gelijktijdig voorkomen van een verhoogde erosiegevoeligheid van de grond. De erosiegevoeligheid van de grond is in het studiegebied sterk afhankelijk van het bodemvochtgehalte, een factor die van dag tot dag verandert. Om de invloed van deze factor op het grondverlies te berekenen moet het bodemvochtgehalte op de dag van een stortbui bekend zijn. Simulatiemodellen kunnen het bodemvochtgehalte op de dag van een stortbui berekenen en bovendien de dagelijkse bedekkingsgraad van de bodem

door mulch en gewas berekenen. De bedekkingsgraad van de bodem is namelijk een volgende factor die grote invloed uitoefent op mogelijk grondverlies. Een dynamisch simulatie model, SHIELD genaamd (Simulation of Hedgerow Intervention against Erosion and Land Degradation) werd ontwikkeld om de effecten van heggen en mulch op afstroming, grondverlies en gewas-opbrengst per dag te berekenen. Een reeds bestaand gewas-simulatiemodel, MAIZE2 genaamd, werd in SHIELD als gewassimulatiemodule gebruikt. SHIELD gebruikt tijdstappen van een dag, maar deze tijdstappen kunnen worden verkort tot de duur van de stortbui door een zogenaamde regenbui-duurtabel. Hiermee kan infiltratie, herverdeling van bodemvocht en afspoeling worden berekend. Hierna wordt het sedimentgehalte van de afstroming per bui berekend, gevolgd door de berekening van het grondverlies per bui. Met SHIELD kan de gebruiker een ontwerp maken, dat gebaseerd is op de optimale afstand tussen de heggen, het aantal bomenrijen in de heg en op het al dan niet strooien van mulch, met behulp van door de gebruiker zelf gedefinieerde randvoorwaarden. SHIELD berekent de haalbare produktie van maïs, hetgeen betekent dat water beperkend kan zijn, maar voedingsstoffen niet. Een toekomstige uitbreiding van SHIELD met modules waarin behalve water ook voedingsstoffen als produktiebeperkende variabelen kunnen worden ingevoerd, zal de toepasbaarheid van dit model alleen maar vergroten. Dat is hard nodig, want watererosie is een probleem dat snel moet worden aangepakt. Een kwantitatieve analyse van het gebruik van anti-erosieheggen om water- en grondverlies te verminderen is van groot belang in de strijd tegen de toenemende bodemdegradatie, die op dit ogenblik een van de belangrijkste bedreigingen vormt voor een goede wereldvoedselvoorziening.

Annex A List of symbols

Symbol	Description	Units
a_h	hedgerow-impact on infiltration parameter	-
a_m	mulch-impact on infiltration parameter	$\text{ha}^{1/2} \text{ t}^{-1/2}$
A	rainfall amount per event	mm
AI_{15}	Lal's erosivity index based on 15-minute intensity	$\text{cm}^2 \text{ h}^{-1}$
AI_{30}	Lal's erosivity index based on 30-minute intensity	$\text{cm}^2 \text{ h}^{-1}$
b_h	barrier-effect parameter of hedgerows	-
$b_{h(n)}$	barrier-effect of hedges with n tree-rows on sediment deposition	-
b_{h+m}	barrier-effect parameter of hedgerows with mulched alleys	-
b_m	barrier-effect parameter of mulch	t ha^{-1}
c	sediment concentration of runoff from the control	kg m^{-3}
c_m	sediment concentration of runoff from a mulched plot	kg m^{-3}
C_o	organic carbon content	-
C_p	specific heat of air at constant pressure	J kg K^{-1}
ΔI_a	infiltration increase in the alley	mm
$\Delta I_{a(m)}$	infiltration increase in the alley with mulch	mm
ΔI_h	infiltration increase beneath the hedgerow	mm
$\Delta I_{h(m)}$	infiltration increase beneath the hedgerow when mulch is applied	mm
$\Delta I_{h(n)}$	infiltration increase beneath a hedge containing n tree-rows	mm
ΔI_{h+a}	weighted average infiltration increase of the hedgerow treatment	mm
$\Delta I_{h(n)+a}$	weighted average infiltration increase in an n -row hedgerow system	mm
ΔI_{h+m}	weighted average infiltration increase in a hedgerow + mulch plot	mm
$\Delta I_{h(n)+m}$	weighted infiltration increase in a mulched n -row hedgerow system	mm
ΔI_m	infiltration increase caused by mulch	mm
d	spacing between successive hedgerows	m
E	Wischmeier's kinetic energy	$\text{t ha}^{-1} \text{ cm}^{-1}$
EI_{15}	Wischmeier's erosivity index based on 15-minute intensity	$\text{t ha}^{-1} \text{ h}^{-1}$
EI_{30}	Wischmeier's erosivity index based on 30-minute intensity	$\text{t ha}^{-1} \text{ h}^{-1}$
E_k	kinetic energy	J
ϕ	slope angle	degrees, %
$F_{c(t)}$	fraction of soil cover by crop at time t	-
$F_{m(t)}$	fraction of soil cover by mulch at time t	-
$F_{T(t)}$	fraction of total soil cover at time t	-
γ	psychrometer constant	kPa K^{-1}
h	seasonal effect of hedgerows on infiltration	-
i	rainfall intensity	mm h^{-1}
I_a	infiltration in the alley	mm
I_c	infiltration in control	mm
I_h	infiltration beneath the hedgerow	mm
$I_{h(n)}$	infiltration beneath a hedge containing n tree-rows	mm
I_{h+a}	weighted average infiltration in the hedgerow barrier system	mm
$I_{h(n)+a}$	weighted average infiltration in the n -row hedgerow barrier system	mm
I_{h+m}	weighted average infiltration in the hedgerow + mulch plot	mm

$I_{h(n)+m}$	weighted average infiltration in the n-row hedge + mulch system	mm
I_m	infiltration in a mulch plot	mm
I_p	gravitational water	mm
j	reduction of the efficacy of additional tree rows on infiltration	-
k	decay constant of mulch	-
λ	volumetric latent heat of vaporization of water	J kg ⁻¹ K ⁻¹
L	plot length	m
LAI	leaf area index	-
LF	landform	m ^{0.5}
M	mulch application	t ha ⁻¹
M_a	molecular weight of air	-
M_w	molecular weight of water vapour	-
n	number of tree-rows per hedgerow	-
p	atmospheric pressure	kPa
P	rainfall	mm
P_{cum}	cumulative rainfall	mm
P_s	seasonal rainfall	mm
P_{24}	daily rainfall	mm
ρ_c	runoff-rainfall ratio from control	-
R_c	runoff from control plot	mm
R_{h+a}	runoff from the hedgerow barrier treatment	mm
$R_{h(n)+a}$	runoff from an n-row hedgerow barrier system	mm
R_{h+m}	runoff from the hedgerow + mulch treatment	mm
$R_{h(n)+m}$	runoff from an n-row hedge + mulch treatment	mm
R_m	runoff from mulch treatment	mm
RI	recurrence interval	d
σ	clod angle	degrees
s	surface storage	mm
S_c	soil loss from control plot	t ha ⁻¹
S_{h+a}	soil loss from hedgerow barrier treatment	t ha ⁻¹
$S_{h(n)+a}$	Soil loss from an n-row hedgerow barrier system	t ha ⁻¹
S_{h+m}	soil loss from hedgerow + mulch treatment	t ha ⁻¹
$S_{h(n)+m}$	Soil loss from an n-row hedgerow + mulch treatment	t ha ⁻¹
S_m	soil loss from mulch treatment	t ha ⁻¹
θ	volumetric soil water content	-
θ_i	antecedent volumetric soil water content	-
θ_s	saturated volumetric soil water content	-
t	time	d
T	daily average temperature	°C
U	specific leaf area	ha t ⁻¹
v	vulnerability of the soil to erosion	mm
w	hedgerow width and zone of increased infiltration	m
z_c	maximum rooting depth of the crop	mm
z_d	surface depression	mm
z_h	maximum rooting depth of the hedgerow	mm
z_i	initial surface depression	mm
Z	altitude	m

Annex B Listing of the SHIELD model

```
DEFINE_CALL ASTRO (INPUT, INPUT, ...  
                   OUTPUT, OUTPUT, OUTPUT, OUTPUT, OUTPUT, OUTPUT)  
DEFINE_CALL DASS (INPUT, INPUT, INPUT, INPUT, INPUT, INPUT, INPUT, ...  
                  INPUT, OUTPUT)  
DEFINE_CALL FUWS (INPUT, INPUT, INPUT, INPUT, INPUT, INPUT, INPUT, ...  
                  INPUT, OUTPUT)  
DEFINE_CALL PRIN (INPUT, INPUT, INPUT, ...  
                  OUTPUT)
```

**TITLE Simulation of Hedgerow Intervention against Erosion and
TITLE Land Degradation - SHIELD.FST ~**

TITLE SHIELD.FST uses KENINT files for weather input

```
*                               * Paul Kiepe, 1995  
  
*                               Grevingaheerd 166  
*                               9737 ST Groningen  
*                               The Netherlands
```

*** S1. PHYSICAL LAND CHARACTERISTICS**

```
INITIAL  
INCON ZERO      = 0.  
PARAMETER ALT   = 1600.  
PARAMETER SLOPE = 8.  
  
PARAMETER TKL1  = 100.  
PARAMETER TKL2  = 200.  
PARAMETER TKL3  = 800.  
PARAMETER TKL4  = 400.  
          TKLT   = TKL1 + TKL2 + TKL3 + TKL4
```

*** M1. SOIL CHARACTERISTICS OF THE MIDDLE ALLEY**

```
PARAMETER WCWPM1 = 0.11  
PARAMETER WCWPM2 = 0.11  
PARAMETER WCWPM3 = 0.16  
PARAMETER WCWPM4 = 0.16  
  
PARAMETER WCADM1 = 0.06  
PARAMETER WCADM2 = 0.06  
PARAMETER WCADM3 = 0.09  
PARAMETER WCADM4 = 0.09
```

PARAMETER WCFCM1 = 0.26
PARAMETER WCFCM2 = 0.26
PARAMETER WCFCM3 = 0.34
PARAMETER WCFCM4 = 0.32

PARAMETER WCSTM1 = 0.40
PARAMETER WCSTM2 = 0.40
PARAMETER WCSTM3 = 0.38
PARAMETER WCSTM4 = 0.37

*** L1. SOIL CHARACTERISTICS OF THE UPPER AND LOWER ALLEY**

PARAMETER WCWPL1 = 0.11
PARAMETER WCWPL2 = 0.11
PARAMETER WCWPL3 = 0.16
PARAMETER WCWPL4 = 0.16

PARAMETER WCADL1 = 0.06
PARAMETER WCADL2 = 0.06
PARAMETER WCADL3 = 0.09
PARAMETER WCADL4 = 0.09

PARAMETER WCFCL1 = 0.26
PARAMETER WCFCL2 = 0.26
PARAMETER WCFCL3 = 0.34
PARAMETER WCFCL4 = 0.32

PARAMETER WCSTL1 = 0.39
PARAMETER WCSTL2 = 0.39
PARAMETER WCSTL3 = 0.38
PARAMETER WCSTL4 = 0.37

*** H1. SOIL CHARACTERISTICS BENEATH THE HEDGEROW**

PARAMETER WCWPH1 = 0.11
PARAMETER WCWPH2 = 0.11
PARAMETER WCWPH3 = 0.16
PARAMETER WCWPH4 = 0.16

PARAMETER WCADH1 = 0.06
PARAMETER WCADH2 = 0.06
PARAMETER WCADH3 = 0.09
PARAMETER WCADH4 = 0.09

PARAMETER WCFCH1 = 0.26
PARAMETER WCFCH2 = 0.26
PARAMETER WCFCH3 = 0.34
PARAMETER WCFCH4 = 0.32

PARAMETER WCSTH1 = 0.42
PARAMETER WCSTH2 = 0.42
PARAMETER WCSTH3 = 0.38
PARAMETER WCSTH4 = 0.37

* S2. SOIL WATER CONTENT

WLM1I = WCLM1I * TKL1
 WLM2I = WCLM2I * TKL2
 WLM3I = WCLM3I * TKL3
 WLM4I = WCLM4I * TKL4
 WCUMMI = WLM1I + WLM2I + WLM3I + WLM4I

INCON WCLM1I = 0.04
 INCON WCLM2I = 0.17
 INCON WCLM3I = 0.20
 INCON WCLM4I = 0.19

WLL1I = WCLL1I * TKL1
 WLL2I = WCLL2I * TKL2
 WLL3I = WCLL3I * TKL3
 WLL4I = WCLL4I * TKL4
 WCUMLI = WLL1I + WLL2I + WLL3I + WLL4I

INCON WCLL1I = 0.04
 INCON WCLL2I = 0.17
 INCON WCLL3I = 0.20
 INCON WCLL4I = 0.19

WLH1I = WCLH1I * TKL1
 WLH2I = WCLH2I * TKL2
 WLH3I = WCLH3I * TKL3
 WLH4I = WCLH4I * TKL4
 WCUMHI = WLH1I + WLH2I + WLH3I + WLH4I

INCON WCLH1I = 0.04
 INCON WCLH2I = 0.11
 INCON WCLH3I = 0.20
 INCON WCLH4I = 0.19

* C2. INITIAL CROP CONDITIONS

* GENOTYPE : KATUMANI COMPOSITE B

LAICI = NCPL * LAIE
 NCPL = 3.7
 INCON LAIE = 1.58E-3

INCON WLVC I = 0.
 INCON WRTC I = 0.
 INCON ZRTC I = 58.

* H2. INITIAL HEDGE CONDITIONS

* SPECIES : CASSIA SIAMEA

LAIHI = NHPL * LAIHAP
 NHPL = 16.

```

INCON LAIHAP      = 3.8E-3
INCON WLVHI       = 0.1E-3
INCON WSTHI       = 0.23
INCON WRTHI       = 0.046
INCON ZRTHI       = 300.

```

* S2. HEDGEROW BARRIER SYSTEM DESIGN

* HEDGEROW DENSITY: SINGLE-ROW

```

PARAMETER HEDDIS = 4.
          HEDWID = TRROWS * 0.25
PARAMETER TRROWS = 1.
PARAMETER LOWAL  = 1.75
          MIDAL  = HEDDIS-HEDWID-LOWAL
          AREAM  = MIDAL/HEDDIS
          AREAL  = LOWAL/HEDDIS
          AREAH  = HEDWID/HEDDIS

```

* C3. CROP DEVELOPMENT

```

DYNAMIC
DVS      = INTGRL(ZERO,DVR)
DVR      = INSW(DVS-1.,DVRV,DVRR) * EMERG
EMERG    = INSW(TIME-DAYEM,0.,1.)
DVRV     = 0.029*(1.-EXP(-0.212*(DDTMP-12.)))
DVRR     = 0.003744 + 0.000491*DDTMP

```

* C4. CROP LEAF CO2 ASSIMILATION

```

AMAXC    = AMXC * AMDVSC * AMTMPC
AMDVSC   = AFGEN(AMDVCT,DVS)
AMTMPC   = AFGEN(AMTMCT,DDTMP)
PARAMETER AMXC = 70.
FUNCTION AMDVCT = 0.0,1.0, 1.2,0.9, 1.6,0.5, 2.0,0.2, 2.5,0.2
FUNCTION AMTMCT = 0.,0., 14.,0.05, 21.,0.8, 23.,0.94,...
              25.,1., 35.,1., 45.,0.75

```

* M5. DAILY GROSS CO2 ASSIMILATION OF THE CROP IN MIDDLE ALLEY

```

CALL ASTRO(DOY,LAT, DAYL,SINLD,COSLD,DSINB,DSINBE,DS0)
CALL DASS(DOY,LAT,RDD,KDF,SCP,LAIM,AMAXC,EFF, DTGAM)
PARAMETER EFF = 0.45
PARAMETER KDF = 0.65
PARAMETER SCP = 0.20

```

* M6. CROP CARBOHYDRATE PRODUCTION

```

GPHOTM    = DTGAM * RDFRLM * PRODFM * 30./44.

```



```

RDFRLM      = LIMIT(0.,1.,(RESMXC-RESLM)/...
              (RESMXC-FEEDBC*RESMXC))
RESLM       = (WRESM/1.49) / (NOTNUL(WSTM))
PARAMETER RESMXC = 0.1
PARAMETER FEEDBC = 0.2

```

* M7. CROP MAINTENANCE

```

MAINTM      = MIN(GPHOTM, MNTSM * TEFF * MNDVSM)
MNTSM       = 0.03*WLVM+0.015*WSTM+0.015*WRTM+0.01*...
              (WCHM+WGRNM)
MNDVSM      = WLVMG / (NOTNUL(WLVM))
TEFF        = Q10**((DAVTMP-35.)/10.)
Q10         = 2.

```

* M8. CROP DRY MATTER PARTITIONING

```

FSHPC       = AFGEN(FSHCTB,DVS)
FSHM        = (FSHPC*PARTFM)/(1.+(PARTFM-1.)*FSHPC)
FRTM        = 1. - FSHM
FUNCTION FSHCTB = 0.,0.4, 0.5,0.5, 0.8,0.6, 1.,0.8, 1.1,1.,...
                2.5,1.

```

```

FLVC        = AFGEN(FLVCTB,DVS)
FSC         = 1. - FLVC
FUNCTION FLVCTB = 0.,1., 0.4,1., 1.2,0., 2.5,0.

```

```

FSTC        = AFGEN(FSTTB, DVS)
FCOB        = 1. - FSTC
FUNCTION FSTTB = 0.,1., 0.9,1., 1.3,0.1, 2.5,0.1

```

```

FCH         = AFGEN(FCHTB,DVS)
FRES        = 1.-FCH
FUNCTION FCHTB = 0.,1., 1.,1., 1.2,0.5, 1.4,0.1, 2.5,0.1

```

* M9. GROWTH OF CROP ORGANS AND RESERVES

```

GTWM        = GPHOTM - MAINTM
GRTM        = FRTM * GTWM / 1.444
GLVM        = FLVC * FSHM * GTWM / 1.463
GSTM        = FSTC * FSC * FSHM * GTWM / 1.513
GCHM        = FCH * FCOB * FSC * FSHM * GTWM / 1.491
GRESM       = FRES * FCOB * FSC * FSHM * GTWM

```

* M10. DEVELOPMENT OF GRAINS

```

GGRM        = MIN(GSINKM, GSOURM)
GSINKM      = NGRNM * 0.01 * PGRI * GRDVS * GRTMP
GRDVS       = AFGEN(GRDVST,DVS)
GRTMP       = AFGEN(GRTMPT,DAVTMP)

```

FUNCTION GRDVST = 0.,0., 1.,0., 1.25,0.15, 1.45,1.,...
 1.55,1., 1.75,0.15, 2.0,0., 2.5,0.
 FUNCTION GRTMPT = 0.,0., 10.,0., 16.,1., 34.,4.

 NGRNM = INTGRL(ZERO,GNGRNM)
 GNGRNM = (NGA * NCPL + NGB * TADRWM) * ...
 INSW(DVS-1., 0., 1.) * INSW(-NGRNM, 0., 1.)
 PARAMETER NGA = -50.
 PARAMETER NGB = 0.5

 PGRI = PKRWT / (0.364 * GFD16)
 PARAMETER PKRWT = 360.
 PARAMETER GFD16 = 50.

 WRESM = INTGRL(ZERO,GWRESM)
 GWRESM = GRESM - DRESM
 DRESM = (GGRM * 1.49)

 GSOURM = (GRESM + WRESM) / 1.49 / TC
 PARAMETER TC = 1.5

*** M11. CROP LEAF DEVELOPMENT**

 LAIM = INSW(TIME-DAYEM,0.,TLAIM)
 TLAIM = INTGRL(LAICI,GLAIM)
 GLAIM = INSW(LAIM-1.0,GLAJC,GLAMM)
 GLAJC = LAICI*RGRCCL*DTEFF*EXP(RGRCCL*TSUMEM)
 PARAMETER RGRCCL = 0.017

 GLAMM = SLAC * (GLVM - DLVM)
 PARAMETER SLAC = 0.0014

 DLVM = WLVMG * INSW (DVS-C1, 0.0, OCLVDF)
 OCLVDF = INSW (DVS-C2, RDR, 0.0)
 PARAMETER C1 = 0.4
 PARAMETER C2 = 2.
 PARAMETER RDR = 0.01

*** M12. CROP DRY MATTER PRODUCTION**

 WRTM = INTGRL(WRTCI,GRTM)
 WLVMG = INTGRL(WLVCI,GWLVMG)
 GWLVMG = GLVM-DLVM
 WLVM = INTGRL(ZERO,DLVM)
 WSTM = INTGRL(ZERO,GSTM)
 WCHM = INTGRL(ZERO,GCHM)
 WGRNM = INTGRL(ZERO,GGRM)

 WLVM = WLVMG + WLVM
 TADRWM = WLVM + WSTM + WCHM + WGRNM + WRESM
 TDRWM = TADRWM + WRTM
 TCOBM = WCHM + WGRNM
 WSTOVM = WLVM+WSTM+WRESM

HIM = WGRNM / (NOTNUL(TADRWM))

*** L5. DAILY GROSS CO2 ASSIMILATION OF THE CROP IN THE UPPER AND LOWER ALLEY**

CALL DASS(DOY,LAT,RDD,KDF,SCP,LAIL,AMAXC,EFF, DTGAL)

*** L6. CROP CARBOHYDRATE PRODUCTION**

GPHOTL = DTGAL * RDFRLL * PRODFL * 30./44.
RDFRLL = LIMIT(0.,1.,(RESMXC-RESLL)/...
(RESMXC-FEEDBC*RESMXC))
RESLL = (WRESL/1.49) / (NOTNUL(WSTL))

*** L7. CROP MAINTENANCE**

MAINTL = MIN(GPHOTL, MNTSL * TEFF * MNDVSL)
MNTSL = 0.03*WLVL+0.015*WSTL+0.015*WRTL+0.01*...
(WCHL+WGRNL)
MNDVSL = WLVLG / (NOTNUL(WLVL))

*** L8. CROP DRY MATTER PARTITIONING**

FSHL = (FSHPC*PARTFL) / (1.+(PARTFL-1.)*FSHPC)
FRTL = 1. - FSHL

*** L9. GROWTH OF CROP ORGANS AND RESERVES**

GTWL = GPHOTL - MAINTL
GRTL = FRTL * GTWL / 1.444
GLVL = FLVC * FSHL * GTWL / 1.463
GSTL = FSTC * FSC * FSHL * GTWL / 1.513
GCHL = FCH * FCOB * FSC * FSHL * GTWL / 1.491
GRESL = FRES * FCOB * FSC * FSHL * GTWL

*** L10. DEVELOPMENT OF GRAINS**

GGRL = MIN(GSINKL,GSOURL)
GSINKL = NGRNL * 0.01 * PGRI * GRDVS * GRTMP
NGRNL = INTGRL(ZERO,GNGRNL)
GNGRNL = (NGA * NCPL + NGB * TADRWL) * ...
INSW(DVS-1., 0., 1.) * INSW(-NGRNL, 0., 1.)
WRESL = INTGRL(ZERO,GWRESL)
GWRESL = GRESL - DRESL
DRESL = (GGRL * 1.49)

GSOURL = (GRESL + WRESL) / 1.49 / TC

*** L11. CROP LEAF DEVELOPMENT**

LAIL = INSW (TIME-DAYEM, 0., TLAIL)
 TLAIL = INTGRL (LAICI, GLAIL)
 GLAIL = INSW (LAIL-1.0, GLAJC, GLAML)

 GLAML = SLAC * (GLVL - DLVL)

 DLVL = WLVLG * INSW (DVS-C1, 0.0, OCLVDF)

*** L12. CROP DRY MATTER PRODUCTION**

WRTL = INTGRL (WRTCI, GRTL)
 WLVLG = INTGRL (WLVC1, GWLVLG)
 GWLVLG = GLVL-DLVL
 WLVD = INTGRL (ZERO, DLVL)
 WSTL = INTGRL (ZERO, GSTL)
 WCHL = INTGRL (ZERO, GCHL)
 WGRNL = INTGRL (ZERO, GGRL)

 WLVL = WLVLG + WLVD
 TADRWL = WLVL + WSTL + WCHL + WGRNL + WRESL
 TDRWL = TADRWL + WRTL
 TCOBL = WCHL + WGRNL
 WSTOVL = WLVL+WSTL+WRESL

 HIL = WGRNL / NOTNUL (TADRWL)

*** H4. HEDGE LEAF CO2 ASSIMILATION**

AMAXH = AMXH * AMDVSH * AMTMPH
 PARAMETER AMXH = 40.
 AMDVSH = AFGEN (AMDVHT, DAD)
 AMTMPH = AFGEN (AMTMHT, DDTMP)
 FUNCTION AMDVHT = 0., 0.01, 1., 1., 21., 1., 120., 1., 240., 0.8
 FUNCTION AMTMHT = 0., 0., 14., 0.05, 21., 0.8, 23., 0.94, ...
 25., 1., 35., 1., 45., 0.75

*** H5. DAILY GROSS CO2 ASSIMILATION OF THE HEDGE**

CALL DASS (DOY, LAT, RDD, KDF, SCP, LAIH, AMAXH, EFF, DTGAH)

*** H6. HEDGE CARBOHYDRATE PRODUCTION**

GPHOTH = DTGAH * RDFRLH * PRODFH * 30./44.
 RDFRLH = LIMIT (0., 1., (RESMXH-RESLH) / (RESMXH-...
 FEEDBH * RESMXH))
 RESLH = (WRESH/1.49) / NOTNUL (WSTH)

PARAMETER RESMXH = 0.20
PARAMETER FEEDBH = 0.75

*** H7. HEDGE MAINTENANCE**

MAINTH = MIN(GPHOTH, MNTSH * TEFF)
MNTSH = $0.03 * WLVH + 0.015 * WSTH + 0.015 * WRTH$

*** H8. HEDGE DRY MATTER PARTITIONING**

FSHPH = AFGEN(FSHHTB,DAD)
FSHH = $(FSHPH * PARTFH) / (1. + (PARTFH - 1.) * FSHPH)$
FRTH = 1. - FSHH
FUNCTION FSHHTB = 0., 0.8, 200., 0.8

FLVH = AFGEN(FLVHTB,DAD)
FSTH = 1. - FLVH
FUNCTION FLVHTB = 0., 0.95, 100., 0.95, 200., 0.95

*** H9. GROWTH OF HEDGE ORGANS AND RESERVES**

GTWH = GPHOTH - MAINTH
GRTH = $FRTH * GTWH / 1.444$
GLVH = $FLVH * FSHH * GTWH / 1.463$
GSTH = $0.8 * FSTH * FSHH * GTWH / 1.513$
GRESH = $0.2 * FSTH * FSHH * GTWH / 1.513$

*** H11. HEDGE LEAF DEVELOPMENT**

LAIH = INSW(DAD-0.5, LAIHI, TLAIH)
TLAIH = INTGRL(LAIHI, GLAIH)
GLAIH = 0.04

*** H12. HEDGE DRY MATTER PRODUCTION**

WRTH = INTGRL(WRTHI, GRTH)
WLVH = INTGRL(WLVHI, GLVH)
WSTH = INTGRL(WSTHI, GSTH)
WRESH = INTGRL(ZERO, GRESH)

TADRWH = WLVH + WSTH
TDRWH = TADRWH + WRTH

*** S13. WEATHER DATA**

DAVTMP = TMMN
RFDUR = TMMX
DDTMP = $1.12 * DAVTMP$

DTEFF = MAX(0., DAVTMP-TBASE)
 TSUMEM = INTGRL(ZERO, DTEFF)
 PARAMETER TBASE = 10.

RRAIN = RAIN
 TRAIN = INTGRL(ZERO, RRAIN)

* S14. PENMAN/MONTEITH (Eo)

PENMAM = EVAPRM + EVAPD
 PENMAL = EVAPRL + EVAPD
 PENMAH = EVAPRH + EVAPD

EVAPRM = (1./LHVAP) * (DELTA/(DELTA+PSYCH)) * NRADM
 EVAPRL = (1./LHVAP) * (DELTA/(DELTA+PSYCH)) * NRADL
 EVAPRH = (1./LHVAP) * (DELTA/(DELTA+PSYCH)) * NRADH
 DELTA = 4.1586 * 1.E3 * SVP / (DAVTMP + 239.)**2
 SVP = 0.611 * EXP(17.4 * DAVTMP/(DAVTMP + 239.))
 LHVAP = (2501. - 2.377 * DAVTMP)*1.E3
 PSYCH = (1.627 * ATMPR/LHVAP)*1.E3
 ATMPR = 101.325*((1.-(2.2569E-5*ALT))**5.2553)

NRADM = (1.-ALBM)* RDD - RLWN
 ALBM = ALBSM*EXP(-0.5*LAIM) + 0.25*...
 (1.-EXP(-0.5*LAIM))
 ALBSM = 0.25 * (1.-0.5*WCLM1/WCSTM1)

NRADL = (1.-ALBL)* RDD - RLWN
 ALBL = ALBSL*EXP(-0.5*LAIL) + 0.25*...
 (1.-EXP(-0.5*LAIL))
 ALBSL = 0.25 * (1.-0.5*WCLL1/WCSTL1)

NRADH = (1.-ALBH)* RDD - RLWN
 ALBH = ALBSH*EXP(-0.5*LAIH) + 0.25*...
 (1.-EXP(-0.5*LAIH))
 ALBSH = 0.25 * (1.-0.5*WCLH1/WCSTH1)

RLWN = FTEMP * FVAP * FCLEAR
 FTEMP = BOLTZM * (DAVTMP+273.)**4
 PARAMETER BOLTZM = 4.9E-3
 FVAP = 0.47-0.209*SQRT(VP)
 FCLEAR = 0.1+0.9*CLEAR
 CLEAR = LIMIT(0., 1., ((RDD/DS0)-ANGSTA)/ANGSTB)
 PARAMETER ANGSTA = 0.25
 PARAMETER ANGSTB = 0.45

WDF = 2.63*(1.0+0.54*WN)
 DRYP = (SVP-VP) * WDF
 EVAPD = (PSYCH/(DELTA+PSYCH)) * DRYP

TEVPRM = INTGRL(ZERO, EVAPRM)
 TEVPRL = INTGRL(ZERO, EVAPRL)
 TEVPRH = INTGRL(ZERO, EVAPRH)
 TEVAPD = INTGRL(ZERO, EVAPD)

*** M15. THE WATER BALANCE OF THE MIDDLE ALLEY**

```

      AINTM      = INSW((RAIN-INTC*LAIM),RAIN,INTC*LAIM)
PARAMETER INTC  = 0.25

      NRAINM     = INSW((RAIN-INTC*LAIM),0.,RAIN-AINTM)

      DPST       = 0.5*ZDPR*SIN(CL-SL)**2*((1./NOTNUL...
                    (TAN(CL+SL)))+(1./NOTNUL(TAN(CL-SL)))/...
                    (2.*NOTNUL(SIN(CL))*COS(CL)*COS(SL)))

      SL         = PI*SLOPE/180.
      CL         = PI*CLD/180.
PARAMETER PI    = 3.1416
PARAMETER CLD   = 50.
      ZDPR       = MAX(12.,INSW(TIME-DOW,ZDPRAP,ZDPAW))
      ZDPRAP     = ZDPRPI/(1.+TDECLF)
      TDECLF     = INTGRL(ZERO,DECLF)
      DECLF      = 0.5*RAIN*(RFINT**2)*1.E-4
      RFINT      = RAIN/NOTNUL(RFDUR)
PARAMETER ZDPRPI = 75.
      ZDPAW      = ZDPRWI/(1.+TDECAW)
      TDECAW     = INTGRL(ZERO,DECLAW)
      DECLAW     = DAWF * DECLF
      DAWF       = INSW(TIME-DOW,0.,1.)
PARAMETER ZDPRWI = 75.

      PINFM      = INSW(INFEVM-NRAINM,INFEVM,NRAINM)
      HOFM       = MAX(0.,NRAINM-PINFM)
      INFEVM     = (DSINFM * RFDUR/24.) + SORPM
      SORPM      = (WCSTM1-WCLM1) * ZEFSOR
PARAMETER ZEFSOR = 100.
      DSINFM     = DSINF* (1.+INFMUL*(MULCH)**0.5)
PARAMETER DSINF  = 206.
PARAMETER INFMUL = 1.4
      MULCH      = MULRT*DECOM** (DAYPR-TIME)*HEDDIS/...
                    (HEDDIS-HEDWID)
PARAMETER DECOM  = 1.04
      MULRT      = APPLIC * INSW(TRROWS-1.5,SHPRUN,DHPRUN)
PARAMETER APPLIC = 1.
      SHPRUN     = CSRUN / HEDDIS
      DHPRUN     = CSRUN / HEDDIS / 0.75
      CSRUN      = (6.06 * PRAIN + 1874.) * 1.E-3
PARAMETER PRAIN  = 222.

      PCLOM1     = MAX(0.,PINFM-(WCFCM1*TKL1-WLM1))
      HCEVM2     = HCONM2 * RFDUR/24.
PARAMETER HCONM2 = 720.
      PCLIM2     = INSW(PCLOM1-HCEVM2,PCLOM1,HCEVM2)
      EXESM1     = MAX(0.,PCLOM1-HCEVM2)

      PCLOM2     = MAX(0.,PCLIM2-(WCFCM2*TKL2-WLM2))
      HCEVM3     = HCONM3 * RFDUR/24.
PARAMETER HCONM3 = 72.
      PCLIM3     = INSW(PCLOM2-HCEVM3,PCLOM2,HCEVM3)
      EXESM2     = MAX(0.,PCLOM2-HCEVM3)

```

PCLOM3	=	MAX (0., PCLIM3 - (WCFCM3*TKL3-WLM3))
HCEVM4	=	HCONM4 * RFDUR/24.
PARAMETER HCONM4	=	72.
PCLIM4	=	INSW (PCLOM3-HCEVM4, PCLOM3, HCEVM4)
EXESM3	=	MAX (0., PCLOM3-HCEVM4)
PCLOM4	=	MAX (0., PCLIM4 - (WCFCM4*TKL4-WLM4))
PARAMETER DRATE	=	12.
DRAINM	=	INSW (PCLOM4-DRATE, PCLOM4, DRATE)
EXESM4	=	MAX (0., PCLOM4-DRATE)
STFLM4	=	INSW (PCLOM4-DRATE, 0., MAX (0., EXESM4-... TKL4* (WCSTM4-WCFCM4)))
STFLM3	=	MAX (0., EXESM3+STFLM4-... TKL3* (WCSTM3-WCFCM3))
STFLM2	=	MAX (0., EXESM2+STFLM3-... TKL2* (WCSTM2-WCFCM2))
SOFM	=	MAX (0., EXESM1+STFLM2-... TKL1* (WCSTM1-WCFCM1))
POFM	=	HOFM+SOFM
RNOFFM	=	INSW (POFM-DPST, 0., POFM-DPST)
DPWATM	=	POFM-RNOFFM
AINFM	=	NRAINM-RNOFFM+DPWATM
DWLM1	=	PINF M+STFLM2-PCLIM2-SOFM-EVSWM1-TRWLM1
DWLM2	=	PCLIM2+STFLM3-PCLIM3-STFLM2-EVSWM2-TRWLM2
DWLM3	=	PCLIM3+STFLM4+DPWATM-PCLIM4-STFLM3-... EVSWM3-TRWLM3
DWLM4	=	PCLIM4-DRAINM-STFLM4-EVSWM4-TRWLM4
WLM1	=	INTGRL (WLM1 I, DWLM1)
WLM2	=	INTGRL (WLM2 I, DWLM2)
WLM3	=	INTGRL (WLM3 I, DWLM3)
WLM4	=	INTGRL (WLM4 I, DWLM4)
WCLM1	=	WLM1/TKL1
WCLM2	=	WLM2/TKL2
WCLM3	=	WLM3/TKL3
WCLM4	=	WLM4/TKL4
RWCLM1	=	(WCLM1-WCWPM1) / (WCFCM1-WCWPM1)
RWCLM2	=	(WCLM2-WCWPM2) / (WCFCM2-WCWPM2)
RWCLM3	=	(WCLM3-WCWPM3) / (WCFCM3-WCWPM3)
RWCLM4	=	(WCLM4-WCWPM4) / (WCFCM4-WCWPM4)
TAINTM	=	INTGRL (ZERO, AINTM)
TAINFM	=	INTGRL (ZERO, AINFM)
TDPWTM	=	INTGRL (ZERO, DPWATM)
TDRNM	=	INTGRL (ZERO, DRAINM)
THOFM	=	INTGRL (ZERO, HOFM)
TSOFM	=	INTGRL (ZERO, SOFM)
TRNOFM	=	INTGRL (ZERO, RNOFFM)
WCUMM	=	WLM1+WLM2+WLM3+WLM4

CHECKM = TRAIN+WCUMMI-TAINTM-TRNOFM-...
WCUMM-TDRNM-TATRNM-TAEVPM

* L15. THE WATER BALANCE OF THE UPPER AND LOWER ALLEY

AINTL = INSW((RAIN-INTC*LAIL),RAIN,INTC*LAIL)
 NRAINL = INSW((RAIN-INTC*LAIL),0.,RAIN-AINTL)
 RUNONL = (RNOFFM*AREAM/NOTNUL(AREAL))+NRAINL
 PINFL = INSW(INFEVL-RUNONL,INFEVL,RUNONL)
 HOFL = MAX(0.,RUNONL-PINFL)
 INFEVL = (DSINFL * RFDUR/24.) + SORPL
 DSINFL = (DSINF A+DSINFH)/2.
 SORPL = (WCSTL1-WCLL1) * ZEFSOR

 PCLOL1 = MAX(0.,PINFL-(WCFCL1*TKL1-WLL1))
 HCEVL2 = HCONL2 * RFDUR/24.
 PARAMETER HCONL2 = 720.
 PCLIL2 = INSW(PCLOL1-HCEVL2,PCLOL1,HCEVL2)
 EXESL1 = MAX(0.,PCLOL1-HCEVL2)

 PCLOL2 = MAX(0.,PCLIL2-(WCFCL2*TKL2-WLL2))
 HCEVL3 = HCONL3 * RFDUR/24.
 PARAMETER HCONL3 = 144.
 PCLIL3 = INSW(PCLOL2-HCEVL3,PCLOL2,HCEVL3)
 EXESL2 = MAX(0.,PCLOL2-HCEVL3)

 PCLOL3 = MAX(0.,PCLIL3-(WCFCL3*TKL3-WLL3))
 HCEVL4 = HCONL4 * RFDUR/24.
 PARAMETER HCONL4 = 144.
 PCLIL4 = INSW(PCLOL3-HCEVL4,PCLOL3,HCEVL4)
 EXESL3 = MAX(0.,PCLOL3-HCEVL4)

 PCLOL4 = MAX(0.,PCLIL4-(WCFCL4*TKL4-WLL4))
 DRAINL = INSW(PCLOL4-DRATE,PCLOL4,DRATE)
 EXESL4 = MAX(0.,PCLOL4-DRATE)

 STFLL4 = INSW(PCLOL4-DRATE,0.,MAX(0.,EXESL4-...
 TKL4*(WCSTL4-WCFCL4)))
 STFLL3 = MAX(0.,EXESL3+STFLL4-...
 TKL3*(WCSTL3-WCFCL3))
 STFLL2 = MAX(0.,EXESL2+STFLL3-...
 TKL2*(WCSTL2-WCFCL2))
 SOFL = MAX(0.,EXESL1+STFLL2-...
 TKL1*(WCSTL1-WCFCL1))

 POFL = HOFL+SOFL
 RNOFFL = INSW(POFL-DPST,0.,POFL-DPST)
 DPWATL = POFL-RNOFFL
 AINFL = RUNONL-RNOFFL+DPWATL

 DWLL1 = PINFL+STFLL2-PCLIL2-SOFL-EVSWL1-TRWLL1*...
 COMPAC-(TRWLL1*COMPAH*LOWAL/HEDWID)
 DWLL2 = PCLIL2+STFLL3-PCLIL3-STFLL2-EVSWL2-...
 TRWLL2* COMPAC-(TRWLL2*COMPAH*LOWAL/HEDWID)

```

DWLL3      = PCLIL3+STFLL4-PCLIL4-STFLL3-EVSWL3-...
            TRWLL3*COMPAC- (TRWLL3*COMPAH*LOWAL/...
            HEDWID)+DPWATL
DWLL4      = PCLIL4-DRAINL-STFLL4-EVSWL4-TRWLL4*...
            COMPAC- (TRWLL4*COMPAH*LOWAL/HEDWID)

WLL1       = INTGRL(WLL1I,DWLL1)
WLL2       = INTGRL(WLL2I,DWLL2)
WLL3       = INTGRL(WLL3I,DWLL3)
WLL4       = INTGRL(WLL4I,DWLL4)

WCLL1      = WLL1/TKL1
WCLL2      = WLL2/TKL2
WCLL3      = WLL3/TKL3
WCLL4      = WLL4/TKL4

RWCLL1     = (WCLL1-WCWPL1)/(WCFCL1-WCWPL1)
RWCLL2     = (WCLL2-WCWPL2)/(WCFCL2-WCWPL2)
RWCLL3     = (WCLL3-WCWPL3)/(WCFCL3-WCWPL3)
RWCLL4     = (WCLL4-WCWPL4)/(WCFCL4-WCWPL4)

TAINTL     = INTGRL(ZERO,AINTL)
TAINFL     = INTGRL(ZERO,AINFL)
TDPWTL     = INTGRL(ZERO,DPWATL)
TDRNL      = INTGRL(ZERO,DRAINL)
THOFL      = INTGRL(ZERO,HOFL)
TSOFL      = INTGRL(ZERO,SOFL)
TRNOFL     = INTGRL(ZERO,RNOFFL)

WCUML      = WLL1+WLL2+WLL3+WLL4
CHECKL     = TRAIN+WCUMLI+(TRNOFM*AREAM/...
            NOTNUL(AREAL))-TAINTL-TRNOFL-...
            WCUML-TDRNL-TATRNL-TAEVPL

```

* H15. THE WATER BALANCE BENEATH THE HEDGEROW

```

AINTH      = INSW((RAIN-INTH*LAIH),RAIN,INTH*LAIH)
PARAMETER INTH      = 0.25
NRAINH     = INSW((RAIN-INTH*LAIH),0.,RAIN-AINTH)
RUNONH     = (RNOFFL*AREAL/NOTNUL(AREAL))+NRAINH
PINFH      = INSW(INFEVH-RUNONH,INFEVH,RUNONH)
INFEVH     = (DSINFH * RFDUR/24.) + SORPH
SORPH      = (WCSTH1-WCLH1) * ZEFSOR
DSINFH     = DSINFH*(1.+INFHED*(HEDDIS-HEDWID))*...
            HEDWID/HEDDIS**2)* 3.* (8.+HEDDIS)/12.
INFHED     = 13.7 * ATRRF
ATRRF      = INSW(TRROWS-0.5,1.,0.75)
HOFH       = MAX(0.,RUNONH-PINFH)

PCLOH1     = MAX(0.,PINFH-(WCFCH1*TKL1-WLH1))
HCEVH2     = HCONH2 * RFDUR/24.
PARAMETER HCONH2    = 1440.
PCLIH2     = INSW(PCLOH1-HCEVH2,PCLOH1,HCEVH2)
EXESH1     = MAX(0.,PCLOH1-HCEVH2)

```

```

PCLOH2      = MAX(0.,PCLIH2-(WCFCH2*TKL2-WLH2))
HCEVH3      = HCONH3 * RFDUR/24.
PARAMETER HCONH3 = 360.
PCLIH3      = INSW(PCLOH2-HCEVH3,PCLOH2,HCEVH3)
EXESH2      = MAX(0.,PCLOH2-HCEVH3)

PCLOH3      = MAX(0.,PCLIH3-(WCFCH3*TKL3-WLH3))
HCEVH4      = HCONH4 * RFDUR/24.
PARAMETER HCONH4 = 360.
PCLIH4      = INSW(PCLOH3-HCEVH4,PCLOH3,HCEVH4)
EXESH3      = MAX(0.,PCLOH3-HCEVH4)

PCLOH4      = MAX(0.,PCLIH4-(WCFCH4*TKL4-WLH4))
DRAINH      = INSW(PCLOH4-DRATE,PCLOH4,DRATE)
EXESH4      = MAX(0.,PCLOH4-DRATE)

STFLH4      = INSW(PCLOH4-DRATE,0.,MAX(0.,EXESH4-...
TKL4*(WCSTH4-WCFCH4)))
STFLH3      = MAX(0.,EXESH3+STFLH4-...
TKL3*(WCSTH3-WCFCH3))
STFLH2      = MAX(0.,EXESH2+STFLH3-...
TKL2*(WCSTH2-WCFCH2))
SOFH        = MAX(0.,EXESH1+STFLH2-...
TKL1*(WCSTH1-WCFCH1))

POFH        = HOFH+SOFH
RNOFFH      = INSW(POFH-DPSH,0.,POFH-DPSH)
PARAMETER DPSH = 5.
DPWATH      = POFH-RNOFFH
AINFH       = RUNONH-RNOFFH+DPWATH

DWLH1       = PINFH+STFLH2-PCLIH2-SOFH-EVSWH1-TRWLH1*...
COMPANH-(TRWLH1*COMPAC*HEDWID/LOWAL)
DWLH2       = PCLIH2+STFLH3-PCLIH3-STFLH2-EVSWH2-...
TRWLH2*COMPANH-(TRWLH2*COMPAC*HEDWID/...
LOWAL)
DWLH3       = PCLIH3+STFLH4-PCLIH4-STFLH3-EVSWH3-...
TRWLH3*COMPANH-(TRWLH3*COMPAC*HEDWID/...
LOWAL)+DPWATH
DWLH4       = PCLIH4-DRAINH-STFLH4-EVSWH4-TRWLH4*...
COMPANH-(TRWLH4*COMPAC*HEDWID/LOWAL)

WLH1        = INTGRL(WLH1I,DWLH1)
WLH2        = INTGRL(WLH2I,DWLH2)
WLH3        = INTGRL(WLH3I,DWLH3)
WLH4        = INTGRL(WLH4I,DWLH4)

WCLH1       = WLH1/TKL1
WCLH2       = WLH2/TKL2
WCLH3       = WLH3/TKL3
WCLH4       = WLH4/TKL4

RWCLH1      = (WCLH1-WCWP1)/(WCFCH1-WCWP1)
RWCLH2      = (WCLH2-WCWP2)/(WCFCH2-WCWP2)

```

```

RWCLH3      = (WCLH3-WCWPH3) / (WCFCH3-WCWPH3)
RWCLH4      = (WCLH4-WCWPH4) / (WCFCH4-WCWPH4)

TAINTH      = INTGRL (ZERO, AINTH)
TAINFH      = INTGRL (ZERO, AINFH)
TDRNH       = INTGRL (ZERO, DRAINH)
THOFH       = INTGRL (ZERO, HOFH)
TSOFH       = INTGRL (ZERO, SOFH)
TRNOFH      = INTGRL (ZERO, RNOFFH)

WCUMH       = WLH1+WLH2+WLH3+WLH4
CHECKH      = TRAIN+WCUMHI+ (TRNOFL*AREAL/NOTNUL...
              (AREAH)) -TAINTH-TRNOFH-WCUMH-TDRNH-...
              TATRNH-TAEVPH

CHECK       = CHECKM+CHECKL+CHECKH

```

* S16. THE SOIL BALANCE

```

AINFC       = AINFM
RUNOFF      = TRNOFH*AREAH/ (AREAM+AREAL+AREAH)
RUNOFH      = RNOFFH*AREAH/ (AREAM+AREAL+AREAH)
RUNOFL      = RNOFFL*AREAL/ (AREAM+AREAL)
TDRAIN      = (TDRNM*AREAM) + (TDRNL*AREAL) + (TDRNH*AREAH)

CRCOVM      = 0.3 * LAIM
CRCOVL      = 0.3 * LAIL
CRCOV       = CRCOVM*AREAM + CRCOVL*AREAL

MLCOV       = IMLCOV * DECOM** (DAYPR-TIME)
IMLCOV      = AFGEN (MLCOVT, MULRT)
FUNCTION MLCOVT = 0., 0., 2., 0.5, 4., 0.75, 6., 0.9, 8., 0.95, ...
              10., 0.98, 12., 1., 20., 1.
SOLCOV      = CRCOV + MLCOV

SLOSS       = INSW (MULRT-BARMUL, SLOSSH, SLOSSM)
PARAMETER BARMUL = 0.10
PARAMETER BARHED = 0.12
SLOSSH      = BARHED*SEDCON*RUNOFH*1.E-2
SLOSSM      = BARMUL*SEDCON*RUNOFH*2.E-2*SQRT (TRROWS/...
              HEDDIS) / SQRT (MULRT)
CALL PRIN (STTIME, TIME, AINFC, PREINF)
SEDCON      = 0.5*RAIN* (RFINT**2) * (TEXTUR*SATFAC/...
              ORGCRB) *NOTNUL (PREINF) *SQRT (LENGTH) *...
              1.E-1* (TAN (SL)) **2 /NOTNUL (CRCOVM)
TEXTUR      = (SILT+SAND) / (CLAY)
PARAMETER SILT = 8.
PARAMETER SAND = 62.
PARAMETER CLAY = 30.
SATFAC      = WCLM1 /WCSTM1

PARAMETER ORGCRB = 0.7
PARAMETER LENGTH = 40.

```

TSLOSS = INTGRL(ZERO, SLOSS)

*** M17. CROP ROOTING DEPTH IN THE MIDDLE ALLEY**

ZRTM = INTGRL(ZRTCI, GZRTM)
GZRTM = GZRTCF*WSER1M*REAAND(ZRTMX-ZRTM, ...
1.0-DVS)*EMERG
WSER1M = INSW(ZRTM-TKL1, WSEM1, WSER2M)
WSER2M = INSW(ZRTM-TKL1-TKL2, WSEM2, WSER3M)
WSER3M = INSW(ZRTM-TKL1-TKL2-TKL3, WSEM3, WSEM4)
PARAMETER GZRTCF = 38.5

ZRTMX = MIN(ZRTMC, ZRTMS, TKLT)
PARAMETER ZRTMS = 1500.
PARAMETER ZRTMC = 1200.

*** M18. CROP TRANSPIRATION**

PTRNSM = (1.-EXP(-0.5*LAIM)) * EVAPRM + EVAPD * ...
MIN(2.5, LAIM) - 0.5 * AINTM
FUNCTION EDPTFT = -.50, 0., -0.05, 0., 0.0, 0.15, 0.15, 0.6, ...
0.30, 0.8, 0.50, 1., 2.5, 1.
ERLBM = ZRTM1*AFGEN(EDPTFT, RWCLM1)+...
ZRTM2*AFGEN(EDPTFT, RWCLM2)+...
ZRTM3*AFGEN(EDPTFT, RWCLM3)+...
ZRTM4*AFGEN(EDPTFT, RWCLM4)
TRRMM = PTRNSM/NOTNUL(ERLBM)

TRWLM1 = TRRMM*WSEM1*ZRTM1*AFGEN(EDPTFT, RWCLM1)
TRWLM2 = TRRMM*WSEM2*ZRTM2*AFGEN(EDPTFT, RWCLM2)
TRWLM3 = TRRMM*WSEM3*ZRTM3*AFGEN(EDPTFT, RWCLM3)
TRWLM4 = TRRMM*WSEM3*ZRTM4*AFGEN(EDPTFT, RWCLM4)

ZRTM1 = LIMIT(0., TKL1, ZRTM)
ZRTM2 = LIMIT(0., TKL2, ZRTM-TKL1)
ZRTM3 = LIMIT(0., TKL3, ZRTM-TKL1-TKL2)
ZRTM4 = LIMIT(0., TKL4, ZRTM-TKL1-TKL2-TKL3)

ATRNSM = TRWLM1+TRWLM2+TRWLM3+TRWLM4

TPTRNM = INTGRL(ZERO, PTRNSM)
TATRNM = INTGRL(ZERO, ATRNSM)

*** M19. SOIL EVAPORATION UNDER CROPS**

PEVAPM = EXP(-0.5*LAIM) * (EVAPRM + EVAPD)

INCON DSLRI = 1.
NDSLRL = INTGRL(DSLRI, DSLR)
DSLRL = INSW(RAIN-0.5, 1., 1.00001-NDSLRL)/DELT

```

AEVAPM      = INSW(NDSLRL-1.1, EVSHM, EVSDM)
EVSHM       = MIN(PEVAPM, (WLM1-WCADM1*TKL1)/DELT+AINFM)
EVSDM       = MIN(PEVAPM, 0.6*PEVAPM*(SQRT(NDSLRL)-...
                SQRT(NDSLRL-1.)))+AINFM)

FEVLM1      = MAX(WLM1-WCADM1*TKL1, 0.1)*EXP(-EES*...
                (0.25*TKL1))
PARAMETER EES = 0.002
FEVLM2      = MAX(WLM2-WCADM2*TKL2, 0.1)*EXP(-EES*...
                (TKL1+(0.25*TKL2)))
FEVLM3      = MAX(WLM3-WCADM3*TKL3, 0.1)*EXP(-EES*...
                (TKL1+TKL2+(0.25*TKL3)))
FEVLM4      = MAX(WLM4-WCADM4*TKL4, 0.1)*EXP(-EES*...
                (TKL1+TKL2+TKL3+(0.25*TKL4)))

FEVLMT      = FEVLM1+FEVLM2+FEVLM3+FEVLM4
EVSWM1      = AEVAPM*(FEVLM1/FEVLMT)
EVSWM2      = AEVAPM*(FEVLM2/FEVLMT)
EVSWM3      = AEVAPM*(FEVLM3/FEVLMT)
EVSWM4      = AEVAPM*(FEVLM4/FEVLMT)

TPEVPM      = INTGRL(ZERO, PEVAPM)
TAEVPM      = INTGRL(ZERO, AEVAPM)

```

*** M20. EFFECTS OF WATER STRESS ON CROP**

```

CALL FUWS(PTRNSM, LAIM, WCLM1, SDRY, SWET, WCWPM1, WCFCM1, ...
          WCSTM1, WSEM1)
CALL FUWS(PTRNSM, LAIM, WCLM2, SDRY, SWET, WCWPM2, WCFCM2, ...
          WCSTM2, WSEM2)
CALL FUWS(PTRNSM, LAIM, WCLM3, SDRY, SWET, WCWPM3, WCFCM3, ...
          WCSTM3, WSEM3)
CALL FUWS(PTRNSM, LAIM, WCLM4, SDRY, SWET, WCWPM4, WCFCM4, ...
          WCSTM4, WSEM4)

PARAMETER SWET = 0.4
PARAMETER SDRY = 0.6

PRODFM      = ATRNSM/NOTNUL(PTRNSM)
PARTFM      = MIN(1., 0.5+ATRNSM/NOTNUL(PTRNSM))

```

*** L17. CROP ROOTING DEPTH IN THE UPPER AND LOWER ALLEY**

```

ZRTL        = INTGRL(ZRTCI, GZRTL)
GZRTL       = GZRTCF*WSER1L*REAAND(ZRTMX-ZRTL, ...
          1.0-DVS)*EMERG
WSER1L      = INSW(ZRTL-TKL1, WSEL1, WSER2L)
WSER2L      = INSW(ZRTL-TKL1-TKL2, WSEL2, WSER3L)
WSER3L      = INSW(ZRTL-TKL1-TKL2-TKL3, WSEL3, WSEL4)

```

* L18. CROP TRANSPIRATION

```

PTRNSL      = (1.-EXP(-0.5*LAIL)) * EVAPRL + EVAPD * ...
              MIN(2.5,LAIL) - 0.5 * AINTL

ERLBL       = ZRTL1*AFGEN(EDPTFT,RWCLL1)+...
              ZRTL2*AFGEN(EDPTFT,RWCLL2)+...
              ZRTL3*AFGEN(EDPTFT,RWCLL3)+...
              ZRTL4*AFGEN(EDPTFT,RWCLL4)

TRRML       = PTRNSL/NOTNUL(ERLBL)

TRWLL1      = TRRML*WSEL1*ZRTL1*AFGEN(EDPTFT,RWCLL1)
TRWLL2      = TRRML*WSEL2*ZRTL2*AFGEN(EDPTFT,RWCLL2)
TRWLL3      = TRRML*WSEL3*ZRTL3*AFGEN(EDPTFT,RWCLL3)
TRWLL4      = TRRML*WSEL3*ZRTL4*AFGEN(EDPTFT,RWCLL4)

ZRTL1       = LIMIT(0.,TKL1,ZRTL)
ZRTL2       = LIMIT(0.,TKL2,ZRTL-TKL1)
ZRTL3       = LIMIT(0.,TKL3,ZRTL-TKL1-TKL2)
ZRTL4       = LIMIT(0.,TKL4,ZRTL-TKL1-TKL2-TKL3)

ATRNSL      = (TRWLL1+TRWLL2+TRWLL3+TRWLL4+((TRWLH1+...
              TRWLH2+TRWLH3+TRWLH4)*HEDWID/LOWAL))*COMPAC
PARAMETER COMPAC = 1.

TPTRNL      = INTGRL(ZERO,PTRNSL)
TATRNL      = INTGRL(ZERO,ATRNSL)

```

* L19. SOIL EVAPORATION UNDER CROPS

```

PEVAPL      = EXP(-0.5*LAIL) * (EVAPRL + EVAPD)

AEVAPL      = INSW(NDSLRL-1.1,EVSHL,EVSDL)
EVSHL       = MIN(PEVAPL,(WLL1-WCADL1*TKL1)/DELT+AINFL)
EVSDL       = MIN(PEVAPL,0.6*PEVAPL*(SQRT(NDSLRL)-...
              SQRT(NDSLRL-1.))+AINFL)

FEVLL1      = MAX(WLL1-WCADL1*TKL1,0.1)*EXP(-EES*...
              (0.25*TKL1))
FEVLL2      = MAX(WLL2-WCADL2*TKL2,0.1)*EXP(-EES*...
              (TKL1+(0.25*TKL2)))
FEVLL3      = MAX(WLL3-WCADL3*TKL3,0.1)*EXP(-EES*...
              (TKL1+TKL2+(0.25*TKL3)))
FEVLL4      = MAX(WLL4-WCADL4*TKL4,0.1)*EXP(-EES*...
              (TKL1+TKL2+TKL3+(0.25*TKL4)))

FEVLLT      = FEVLL1+FEVLL2+FEVLL3+FEVLL4
EVSWL1      = AEVAPL*(FEVLL1/FEVLLT)
EVSWL2      = AEVAPL*(FEVLL2/FEVLLT)
EVSWL3      = AEVAPL*(FEVLL3/FEVLLT)
EVSWL4      = AEVAPL*(FEVLL4/FEVLLT)

TPEVPL      = INTGRL(ZERO,PEVAPL)
TAEVPL      = INTGRL(ZERO,AEVAPL)

```

*** L20. EFFECTS OF WATER STRESS ON CROP**

```
CALL FUWS (PTRNSL, LAIL, WCLL1, SDRY, SWET, WCWPL1, WCFCL1, ...
           WCSTL1, WSEL1)
CALL FUWS (PTRNSL, LAIL, WCLL2, SDRY, SWET, WCWPL2, WCFCL2, ...
           WCSTL2, WSEL2)
CALL FUWS (PTRNSL, LAIL, WCLL3, SDRY, SWET, WCWPL3, WCFCL3, ...
           WCSTL3, WSEL3)
CALL FUWS (PTRNSL, LAIL, WCLL4, SDRY, SWET, WCWPL4, WCFCL4, ...
           WCSTL4, WSEL4)
```

```
PRODFL      = ATRNSL/NOTNUL (PTRNSL)
PARTFL      = MIN(1., 0.5+ATRNSL/NOTNUL (PTRNSL))
```

*** H17. CROP ROOTING DEPTH OF THE HEDGE**

```
ZRTH        = INTGRL (ZRTH1, GZRTH)
GZRTH       = GZRTHF*WSER1H
WSER1H      = INSW (ZRTH-TKL1, WSEH1, WSER2H)
WSER2H      = INSW (ZRTH-TKL1-TKL2, WSEH2, WSER3H)
WSER3H      = INSW (ZRTH-TKL1-TKL2-TKL3, WSEH3, WSEH4)
PARAMETER GZRTHF = 0.5
```

*** H18. HEDGE TRANSPIRATION**

```
PTRNSH      = (1.-EXP(-0.5*LAIH)) * EVAPRH + EVAPD * ...
              MIN(2.5, LAIH) - 0.5 * AINTH
ERLBH       = ZRTH1*AFGEN (EDPTFT, RWCLH1) + ...
              ZRTH2*AFGEN (EDPTFT, RWCLH2) + ...
              ZRTH3*AFGEN (EDPTFT, RWCLH3) + ...
              ZRTH4*AFGEN (EDPTFT, RWCLH4)
TRRMH       = PTRNSH/NOTNUL (ERLBH)

TRWLH1      = TRRMH*WSEH1*ZRTH1*AFGEN (EDPTFT, RWCLH1)
TRWLH2      = TRRMH*WSEH2*ZRTH2*AFGEN (EDPTFT, RWCLH2)
TRWLH3      = TRRMH*WSEH3*ZRTH3*AFGEN (EDPTFT, RWCLH3)
TRWLH4      = TRRMH*WSEH3*ZRTH4*AFGEN (EDPTFT, RWCLH4)

ZRTH1       = LIMIT (0., TKL1, ZRTH)
ZRTH2       = LIMIT (0., TKL2, ZRTH-TKL1)

ZRTH3       = LIMIT (0., TKL3, ZRTH-TKL1-TKL2)
ZRTH4       = LIMIT (0., TKL4, ZRTH-TKL1-TKL2-TKL3)

ATRNSH      = (TRWLH1+TRWLH2+TRWLH3+TRWLH4+((TRWLL1+...
              TRWLL2+TRWLL3+TRWLL4)*LOWAL/HEDWID))*COMPAH
PARAMETER COMPAH = 0.05

TPTRNH      = INTGRL (ZERO, PTRNSH)
TATRNH      = INTGRL (ZERO, ATRNSH)
```


* H19. SOIL EVAPORATION UNDER THE HEDGE

```

PEVAPH      = EXP(-0.5*LAIH) * (EVAPRH + EVAPD)

AEVAPH      = INSW(NDSLR-1.1, EVSHH, EVSDH)
EVSHH       = MIN(PEVAPH, (WLH1-WCADH1*TKL1)/DELT+AINFH)
EVSDH       = MIN(PEVAPH, 0.6*PEVAPH*(SQRT(NDSLR)-...
                  SQRT(NDSLR-1.))+AINFH)

FEVLH1      = MAX(WLH1-WCADH1*TKL1, 0.1)*EXP(-EES*...
                  (0.25*TKL1))
FEVLH2      = MAX(WLH2-WCADH2*TKL2, 0.1)*EXP(-EES*...
                  (TKL1+(0.25*TKL2)))
FEVLH3      = MAX(WLH3-WCADH3*TKL3, 0.1)*EXP(-EES*...
                  (TKL1+TKL2+(0.25*TKL3)))
FEVLH4      = MAX(WLH4-WCADH4*TKL4, 0.1)*EXP(-EES*...
                  (TKL1+TKL2+TKL3+(0.25*TKL4)))

FEVLHT      = FEVLH1+FEVLH2+FEVLH3+FEVLH4
EVSWH1      = AEVAPH*(FEVLH1/FEVLHT)
EVSWH2      = AEVAPH*(FEVLH2/FEVLHT)
EVSWH3      = AEVAPH*(FEVLH3/FEVLHT)
EVSWH4      = AEVAPH*(FEVLH4/FEVLHT)

TPEVPH      = INTGRL(ZERO, PEVAPH)
TAEVPH      = INTGRL(ZERO, AEVAPH)

```

* H20. EFFECTS OF WATER STRESS ON THE HEDGE

```

CALL FUWS(PTRNSH, LAIH, WCLH1, SDRY, SWET, WCWPH1, WCFCH1, ...
          WCSTH1, WSEH1)
CALL FUWS(PTRNSH, LAIH, WCLH2, SDRY, SWET, WCWPH2, WCFCH2, ...
          WCSTH2, WSEH2)
CALL FUWS(PTRNSH, LAIH, WCLH3, SDRY, SWET, WCWPH3, WCFCH3, ...
          WCSTH3, WSEH3)
CALL FUWS(PTRNSH, LAIH, WCLH4, SDRY, SWET, WCWPH4, WCFCH4, ...
          WCSTH4, WSEH4)

PRODFH      = ATRNSH/NOTNUL(PTRNSH)
PARTFH      = MIN(1., 0.5+ATRNSH/NOTNUL(PTRNSH))

```

* S22. CROP PRODUCTION IN THE HEDGEROW BARRIER SYSTEM

```

WGRAIN      = WGRNM*AREAM + WGRNL*AREAL
TCOB        = TCOBM*AREAM + TCOBL*AREAL
WSTOV       = WSTOVM*AREAM + WSTOVL*AREAL
TADRWC      = TADRWM*AREAM + TADRWL*AREAL

```

* S23. RUN CONTROL

```

PARAMETER DAYPR = 303.
PARAMETER DAYEM = 309.

```

```

        DAE          = MAX(0.,TIME-DAYEM)
PARAMETER DOW        = 345.
        DAP          = MAX(0.,TIME-DAYPR)
        DORM1        = (DAVTMP-TBASE)
        DORM2        = INTGRL(ZERO,DORM1)
        DORM3        = INSW(DORM2-TMPSUM,0.,1.)
PARAMETER TMPSUM     = 150.
        DAD          = INTGRL(ZERO,DORM3)
        DAY          = DOY

FINISH CHECK         > 1.E-3
FINISH DVS           > 2.

TIMER STTIME        = 303., FINTIM = 500., DELT=1., PRDEL=1.

WEATHER WTRDIR      ='C:\SYS\WEATHER\' , CNTR='KENINT' , ISTN=2,...
                    IYEAR=1992

TRANSLATION_FSE

PRINT RUNOFF,TSLOSS,WGRAIN

END
STOP
ENDJOB

```

Annex C Listing of subroutines used in SHIELD

```

* -----
* subroutine DASS
* computes potential daily assimilation (DTGA, kg CO2/ha/d)
* -----
      SUBROUTINE DASS (DOY,LAT,RDD,KDF,SCP,LAI,AMAX,EFF,
$                   DTGA)
      IMPLICIT REAL (A-Z)
      INTEGER T
* distances and weights in Gaussian integration
      DIMENSION GSDST(3), GSWT(3)
      DATA GSDST/0.112702, 0.5, 0.887298/
      DATA GSWT /0.277778,0.444444,0.277778/
* daylength (h) and daily extra-terrestrial radiation
* (J/m2/d)
      CALL ASTRO (DOY,LAT,
$              DAYL,SINLD,COSLD,DSINB,DSINBE,DS0)
* daily radiation above the canopy (J/m2/d)
      CALL DRADIA (DS0,RDD,
$              FRDF,DPAR)

      DTGA = 0.
      DO 100 T = 1,3
          HOUR = 12. + DAYL*0.5*GSDST(T)
          CALL ASS (HOUR,DAYL,SINLD,COSLD,DSINB,DSINBE,RDD,
$              FRDF,DPAR,KDF,SCP,LAI,AMAX,EFF,
$              FGROS)
* integration of instantaneous assimilation to a daily total
* (DTGA)
          DTGA = DTGA + FGROS * DAYL * GSWT(T)
100 CONTINUE
      RETURN
      END

* -----
* Subroutine ASTRO
* computes daylength and daily extra-terrestrial radiation
* from daynumber and latitude
* -----
      SUBROUTINE ASTRO (DOY,LAT,
$                   DAYL,SINLD,COSLD,DSINB,DSINBE,DS0)
      IMPLICIT REAL (A-Z)
* conversion factor from degrees to radians
      PI = 3.1415926
      RD = PI / 180.
* declination (DEC, degrees) of the sun as a function of day
* (DOY)
      DEC = -ASIN (SIN(23.45*RD) * COS(2.*PI*(DOY+10.)/365.))/RD
      SINLD = SIN(LAT*RD) * SIN(DEC*RD)
      COSLD = COS(LAT*RD) * COS(DEC*RD)
* daylength (DAYL, h)
      DAYL = 12. * (1.+2. * ASIN(SINLD/COSLD)/PI)
* daily integral of sine of solar inclination (DSINB)

```

```

    DSINB = 3600.* (DAYL * SINLD+ 24.* COSLD *
$      SQRT(1.- (SINLD/COSLD)**2) / PI)
*   daily integral of SINB with a correction for lower
*   atmospheric transmission at lower solar elevations (DSINBE)
    DSINBE = 3600.* (DAYL * (SINLD + 0.4* (SINLD * SINLD + 0.5
$      * COSLD * COSLD))+ 12.* COSLD* (2.+3.*0.4*SINLD)
$      * SQRT(1.- (SINLD/COSLD)**2)/PI)
*   daily extra-terrestrial radiation (DS0, J/m2/d) from
*   corrected solar constant (SC, J/m2/s)
    SC = 1370. * (1.+0.033*COS(2.*PI*DOY/365.))
    DS0= SC * DSINB
    RETURN
    END

* -----
* Subroutine DRADIA:
* computes daily photosynthetically active radiation (DPAR) and
* diffuse fraction of incoming radiation (FRDF)
* from atmospheric radiation transmission
* -----
    SUBROUTINE DRADIA (DS0,RDD,
$      FRDF,DPAR)
    IMPLICIT REAL (A-Z)
*   daily photosynthetically active radiation (J/m2/d)
    DPAR = 0.50 * RDD
*   fraction diffuse radiation (FRDF) from atmospheric
*   transmission (ATMTR)
    ATMTR = RDD / DS0
    FRDF=0.23
    IF(ATMTR.LE.0.75) FRDF=1.33-1.46*ATMTR
    IF(ATMTR.LE.0.35) FRDF=1.-2.3*(ATMTR-0.07)**2
    IF(ATMTR.LE.0.07) FRDF=1.
    RETURN
    END

* -----
* Subroutine ASS
* calculates instantaneous assimilation (FGROS, kg CO2/ha/h)
* -----
    SUBROUTINE ASS (HOUR,DAYL,SINLD,COSLD,DSINB,DSINBE,RDD,
$      FRDF,DPAR,KDF,SCP,LAI,AMAX,EFF,
$      FGROS)
    IMPLICIT REAL (A-Z)
    INTEGER L,I2
    DIMENSION GSDST(3), GSWT(3)
    DATA GSDST /0.112702, 0.5, 0.887298/
    DATA GSWT /0.277778,0.444444,0.277778/

*   radiation above the canopy PAR (J/m2/s)
    CALL RADIAT (HOUR,SINLD,COSLD,DSINB,DSINBE,FRDF,DPAR,
$      PARDF,PARDR,SINB)

*   canopy reflection coefficient (REFL)
    REFL = (1. - SQRT(1.-SCP)) / (1. + SQRT(1.-SCP))
*   extinction coefficient for direct component(KBL) and total

```

```

*      direct flux (KDRT) and the cluster factor
      CLUSTF = KDF / (0.8*SQRT(1.-SCP))
      KBL = (0.5/SINB) * CLUSTF
      KDRT= KBL * SQRT(1.-SCP)

*      selection of canopy depths (LAIC from top)
      FGROS = 0.
      DO 200 L = 1,3
        LAIC = LAI * GSDST(L)

*      absorbed radiation fluxes per unit leaf area (J/m2/s):
*      diffuse flux, total direct flux, direct component of direct
*      flux
      PARLDF = (1.-REFL) * PARDF * KDF * EXP(-KDF * LAIC)
      PARLT  = (1.-REFL) * PARDR * KDRT * EXP(-KDRT * LAIC)
      PARLDR = (1.-SCP) * PARDR * KBL * EXP(-KBL * LAIC)

*      absorbed fluxes (J/m2 leaf/s) for shaded and sunlit leaves
      PARLSH = PARLDF + (PARLT - PARLDR)
*      direct par absorbed by leaves perpendicular on direct beam
      PARLPP = PARDR * (1.-SCP)/SINB

*      fraction sunlit leaf area
      FSLLA = CLUSTF*EXP(-KBL*LAIC)

*      assimilation of shaded leaf area (kg CO2/ha leaf/hr)
      ASSSH = AMAX * (1.-EXP(-EFF*PARLSH/AMAX))
*      assimilation of sunlit leaf area (kg CO2/ha leaf/hr)
      ASSSL=0.
      DO 210 I2=1,3
        PARLSL = PARLSH + PARLPP * GSDST(I2)
        ASSSL  = ASSSL + AMAX * (1. - EXP(-PARLSL * EFF / AMAX))
      $      * GSWT(I2)
210  CONTINUE

*      hourly total gross assimilation (kg CO2/ha soil/hr)
      FGROS = FGROS + ((1.-FSLLA) * ASSSH + FSLLA * ASSSL) *
      $      LAI * GSWT(L)
200  CONTINUE
      RETURN
      END

* -----
* Subroutine RADIAT
* computes instantaneous radiation above the canopy (J/m2/s)
* -----
      SUBROUTINE RADIAT (HOUR,SINLD,COSLD,DSINB,DSINBE,FRDF,DPAR,
      $      PARDF,PARDR,SINB)
      IMPLICIT REAL (A-Z)
      PI = 3.1415926
*      sine of solar inclination (SINB)
      SINB = MAX(0.,SINLD+COSLD*COS(2.*PI*(HOUR+12.)/24.))
*      diffuse PAR (PARDF) and direct PAR (PARDR) in J/m2/s
      PAR = DPAR * SINB * (1.+0.4*SINB) / DSINBE
      PARDF = MIN(PAR, FRDF * DPAR * SINB/DSINB)

```

```

PARDR = PAR - PARDF
RETURN
END

```

```

* -----
* Subroutine FUWS
* computes factors accounting for water stress effect WSE
* -----

```

```

SUBROUTINE FUWS (PTRNS, LAI, WCL, SDRY, SWET, WCWP, WCFC, WCST,
$              WSE)
IMPLICIT REAL (A-Z)
DATA A,B,LAIMX/0.76,0.15,2./
IF (WCL .LE. WCFC) THEN
  SWPF = 1./ (A+B*LAIMX*PTRNS/(LAI+1.E-10)) - (1.-SDRY)*0.4
IF (SDRY.LT.0.6) THEN
  SWPF = SWPF+0.025*MIN(0.,LAIMX*PTRNS/(LAI+1.E-10)-6.)/
$      (1.+5.*SDRY+4.*SDRY*SDRY)
ENDIF
WCDRY = WCWP+(WCFC-WCWP)*(1.00-MIN(1.,MAX(0.,SWPF)))
FUWSX = (WCL-WCWP)/(WCDRY-WCWP+1.E-10)
ELSE
  WCWET = WCFC + SWET*(WCST-WCFC)
  FUWSX = (WCL-WCST)/(WCWET-WCST+1.E-10)
ENDIF
WSE = MIN(1.,MAX(0.,FUWSX))
RETURN
END

```

```

* -----
* Subroutine PRIN
* computes gravitational water by calculating the cumulative
* infiltration of the two preceding days, which is used to
* estimate the sediment concentration in runoff
* -----

```

```

SUBROUTINE PRIN (STIME, TIME, AINFC,
$              PREINF)
IMPLICIT REAL (A-Z)
IF (TIME.EQ.STIME) THEN
  AINFC1 = 0.
  AINFC2 = 0.
ENDIF
PREINF = AINFC1 + AINFC2
AINFC2 = AINFC1
AINFC1 = AINFC
RETURN
END

```

Annex D Glossary of terms used in SHIELD

Name	Description	Units
AEVAPH	Actual soil evaporation rate beneath the hedgerow	mm d ⁻¹
AEVAPL	Actual soil evaporation rate of the lower alley	mm d ⁻¹
AEVAPM	Actual soil evaporation rate of the middle alley	mm d ⁻¹
AINFH	Actual infiltration beneath the hedgerow	mm
AINFL	Actual infiltration of the lower alley	mm
AINFM	Actual infiltration of the middle alley	mm
AINTH	Actual rainfall interception of the hedgerow	mm d ⁻¹
AINTL	Actual rainfall interception in the lower alley	mm d ⁻¹
AINTM	Actual rainfall interception in the middle alley	mm d ⁻¹
ALBH	Albedo of the hedgerow	-
ALBL	Albedo of the lower alley	-
ALBM	Albedo of the middle alley	-
ALBSH	Albedo for the soil surface beneath the hedgerow	-
ALBSL	Albedo for the soil surface of the lower alley	-
ALBSM	Albedo for the soil surface of the middle alley	-
ALT	Altitude	m
AMAXC	Actual leaf CO ₂ assimilation rate of the crop	kg ha ⁻¹ leaf h ⁻¹
AMAXH	Actual leaf CO ₂ assimilation rate of the hedge	kg ha ⁻¹ leaf h ⁻¹
AMDVCT	Table of AMDVSC as function of DVS	-, -
AMDVHT	Table of AMDVSH as function of DAD	-, d
AMDVSC	Factor accounting for aging of crop leaves	-
AMDVSH	Factor accounting for aging of hedge leaves	-
AMTMCT	Table of AMTMPC as function of DDTMP	-, °C
AMTMHT	Table of AMTMPH as function of DDTMP	-, °C
AMTMPC	Daytime temperature effect on AMXC	-
AMTMPH	Daytime temperature effect on AMXH	-
AMXC	Potential crop leaf CO ₂ assimilation rate	kg ha ⁻¹ leaf h ⁻¹
AMXH	Potential hedge leaf CO ₂ assimilation rate	kg ha ⁻¹ leaf h ⁻¹
ANGSTA	Ångström parameter A	-
ANGSTB	Ångström parameter B	-
APPLIC	Application fraction of mulch	-
AREAH	Fraction of land under hedgerows	-
AREAM	Fraction of land as middle alley	-
AREAL	Fraction of land as lower alley	-
ASS	Subroutine that computes instantaneous assimilation rate	-
ASTRO	Subroutine that computes day length and Angot-value	-
ATMPR	Ambient atmospheric pressure	kPa
ATRANSH	Actual daily transpiration of hedgerow canopy	mm d ⁻¹
ATRANSM	Actual daily transpiration of crop canopy in middle alley	mm d ⁻¹
ATRANSL	Actual daily transpiration of crop canopy in lower alley	mm d ⁻¹
ATTRF	Additional tree-row reduction factor on infiltration	-

BARHED	Barrier-effect parameter of hedgerows	-
BARMUL	Barrier-effect parameter of mulch	$t\ ha^{-1}$
BOLTZM	Boltzman constant	$J\ m^{-2}\ d^{-1}\ K^{-4}$
CHECK	Algorithm to check the total water balance	$mm\ d^{-1}$
CHECKH	Algorithm to check the water balance beneath the hedge	$mm\ d^{-1}$
CHECKL	Algorithm to check the water balance in the lower alley	$mm\ d^{-1}$
CHECKM	Algorithm to check the water balance in the middle alley	$mm\ d^{-1}$
CL	Clod angle	rad
CLAY	Percentage clay in topsoil	-
CLD	Clod angle	degrees
CLEAR	Penman's clearness factor	-
COMPAC	Competitive advantage of the crop	-
COMPAH	Competitive advantage of the hedgerow	-
CRCOV	Soil cover ratio of crop	-
CRCOVL	Soil cover ratio of crop in the lower alley	-
CRCOVM	Soil cover ratio of crop in the middle alley	-
CSPRUN	Production of <i>Cassia siamea</i> prunings	$t\ ha^{-1}$
C1	Threshold value of DVS used in DLV computation	-
C2	Threshold value of DVS used in DLV computation	-
DAD	Days after dormancy of the hedgerow	d
DAE	Days after emergence of the crop	d
DAP	Days after pruning of the hedgerow	d
DASS	Subroutine that calculates potential daily assimilation	-
DAVTMP	Daily average temperature	$^{\circ}C$
DAWF	Days after weeding switch	-
DAFWF	Days after first weeding switch	-
DASWF	Days after second weeding switch	-
DAY	Day of year as used in SHIELD	d
DAYEM	Julian day of emergence	d
DAYPR	Julian day of pruning	d
DDTMP	Daily average daytime temperature	$^{\circ}C$
DECOM	Parameter for the rate of mulch decomposition	-
DECLF	Decline factor of surface depression	-
DECLAW	Decline of surface depression after weeding	-
DECLFW	Decline of surface depression after first weeding	-
DECLSW	Decline of surface depression after second weeding	-
DELTA	Tangent between SVP and temperature	$kPa\ ^{\circ}C^{-1}$
DHPRUN	Pruning production in double-row hedges	$t\ ha^{-1}$
DSINFA	Daily steady state infiltration rate in the total alley	$mm\ d^{-1}$
DSINFH	Daily steady state infiltration rate beneath the hedge	$mm\ d^{-1}$
DSINFL	Daily steady state infiltration rate in the lower alley	$mm\ d^{-1}$
DSINFM	Daily state steady infiltration rate under mulch	$mm\ d^{-1}$
DLVL	Death rate of crop leaves in the lower alley	$kg\ ha^{-1}\ d^{-1}$
DLVM	Death rate of crop leaves in the middle alley	$kg\ ha^{-1}\ d^{-1}$
DORM1-3	Auxiliary parameters to calculate dormancy	d
DOW	Day of weeding	-

DOFW	Day of first weeding	-
DOSW	Day of second weeding	-
DOY	Day of year as used in SUCROS	d
DPST	Surface depression storage	mm
DPWATL	Water trapped in surface depression in the lower alley	mm
DPWATM	Water trapped in surface depression in the middle alley	mm
DRADIA	Subroutine that calculates photosynthetic active radiation	-
DRAINH	Actual drainage from the soil profile beneath the hedge	mm d ⁻¹
DRAINL	Actual drainage from the soil profile of the lower alley	mm d ⁻¹
DRAINM	Actual drainage from the soil profile of the middle alley	mm d ⁻¹
DRATE	Maximum drainage rate from the soil profile	mm d ⁻¹
DRESL	Depletion rate of lower-alley crop carbohydrate reserves	kg ha ⁻¹ d ⁻¹
DRESM	Depletion rate of middle-alley carbohydrate reserves	kg ha ⁻¹ d ⁻¹
DRYP	Drying power of the atmosphere	mm d ⁻¹
DSLRL	Number of days since last rain	d
DSLRI	Initial number of days since last rain	d
DSO	Daily extra-terrestrial radiation	J m ⁻² d ⁻¹
DTEFF	Daily temperature effect	°C
DTGAH	Daily total gross hedge assimilation rate	kg CO ₂ ha ⁻¹ d ⁻¹
DTGAL	Daily total gross lower-alley crop assimilation rate	kg CO ₂ ha ⁻¹ d ⁻¹
DTGAM	Daily total gross middle-alley crop assimilation rate	kg CO ₂ ha ⁻¹ d ⁻¹
DTR	Daily total radiation	J m ⁻² d ⁻¹
DVR	Development rate of crop	d ⁻¹
DVRR	Development rate in reproductive stage	d ⁻¹
DVRV	Development rate in vegetative stage	d ⁻¹
DVS	Development stage	-
DWLH1-4	Daily changes in soil water in hedge layer 1-4	mm
DWLL1-4	Daily changes in soil water in the lower-alley layer 1-4	mm
DWLM1-4	Daily changes in soil water in the middle-alley layer 1-4	mm
EDPTFT	Table for the root activity coefficient	-, -
EES	Evaporation extinction coefficient for the soil	mm ⁻¹
EFF	Initial light use efficiency for leaves	kg CO ₂ ha ⁻¹ h ⁻¹
EMERG	Parameter to indicate emergence	-
ERLBL	Total effect of crop root length in the lower alley	mm
ERLBM	Total effect of crop root length in the middle alley	mm
EVAPD	Penman's drying power term	mm d ⁻¹
EVAPRH	Penman's radiation term in the hedgerow	mm d ⁻¹
EVAPRL	Penman's radiation term in the lower alley	mm d ⁻¹
EVAPRM	Penman's radiation term in the middle alley	mm d ⁻¹
EVSDH	Evaporation rate on a dry day from the hedgerow	mm d ⁻¹
EVSDL	Evaporation rate on a dry day from the lower alley	mm d ⁻¹
EVSDM	Evaporation rate on a dry day from the middle alley	mm d ⁻¹
EVSHH	Evaporation rate on a humid day from the hedgerow	mm d ⁻¹
EVSHL	Evaporation rate on a humid day from the lower alley	mm d ⁻¹
EVSHM	Evaporation rate on a humid day from the middle alley	mm d ⁻¹
EVSWH1-4	Evaporation rate from soil layer 1-4 of hedge	mm d ⁻¹
EVSWL1-4	Evaporation rate from soil layer 1-4 of lower-alley	mm d ⁻¹

EVSWM1-4	Evaporation rate from soil layer 1-4 of middle-alley	mm d ⁻¹
EXESH1-4	Excess soil water beneath the hedge in layer 1-4	mm
EXESL1-4	Excess soil water of the lower alley in layer 1-4	mm
EXESM1-4	Excess soil water of the middle alley in layer 1-4	mm
FCH	Fraction of dry matter allocated to chaff	-
FCHTB	Table of FCH as function of DVS	-, -
FCLEAR	Sky clearness function in calculation of radiation	-
FCOB	Fraction of dry matter allocated to cobs	-
FEEDBC	Feedback in crop assimilation if reserves are formed	-
FEEDBH	Feedback in hedge assimilation if reserves are formed	-
FEVLH1-4	Fraction of soil water extraction from hedge layer 1-4	-
FEVLHT	Total soil water extraction beneath the hedge	-
FEVLL1-4	Fraction of water extraction from lower-alley layer 1-4	-
FEVLLT	Total soil water extraction in the lower alley	-
FEVLM1-4	Fraction of water extraction from middle-alley layer 1-4	-
FEVLMT	Total soil water extraction in the middle alley	-
FLVC	Fraction of dry matter allocated to crop leaves	-
FLVH	Fraction of dry matter allocated to hedge leaves	-
FLVCTB	Table of FLVC as function of DVS	-, -
FLVHTB	Table of FLVH as function of DAD	-, d
FRES	Fraction of crop dry matter allocated to reserves	-
FRTH	Fraction of hedge dry matter allocated to roots	-
FRTL	Ratio of dry matter allocated to lower-alley crop roots	-
FRTM	Ratio of dry matter allocated to middle-alley crop roots	-
FSC	Fraction of crop dry matter allocated to stem and cobs	-
FSHCTB	Table of FSHC as function of DVS	-, -
FSHH	Fraction of hedge dry matter allocated to shoots	-
FSHHTB	Table of FSHH as function of DAD	-, d
FSHL	Ratio of dry matter allocated to lower alley-crop shoots	-
FSHM	Ratio of dry matter allocated to middle alley-crop shoots	-
FSHPC	Fraction of potential crop dry matter allocated to shoots	-
FSHPH	Fraction of potential hedge dry matter allocated to shoot	-
FSTC	Fraction of crop dry matter allocated to stems	-
FSTH	Fraction of hedge dry matter allocated to stems	-
FSTTB	Table of FSTC as function of DVS	-, -
FTEMP	Temperature factor in Penman	-
FUWS	Subroutine that calculates water stress	-
FVAP	Vapour pressure effect on RWLN (Brunt equation)	-
GCHL	Growth rate of chaff in lower alley	kg DM ha ⁻¹ d ⁻¹
GCHM	Growth rate of chaff in middle alley	kg DM ha ⁻¹ d ⁻¹
GFD16	Grain filling duration period	d
GGRL	Growth rate of grains in lower alley	kg DM ha ⁻¹ d ⁻¹
GGRM	Growth rate of grains in middle alley	kg DM ha ⁻¹ d ⁻¹
GLAIH	Growth rate of hedge leaf area index	d ⁻¹
GLAIL	Growth rate of crop leaf area index in the lower alley	d ⁻¹
GLAIM	Growth rate of crop leaf area index in the middle alley	d ⁻¹

GLAJC	Growth rate of crop leaf area index in juvenile stage	d^{-1}
GLAML	Growth rate of mature crop leaf area index, lower alley	d^{-1}
GLAMM	Growth rate of mature crop leaf area index, middle alley	d^{-1}
GLVH	Growth rate of hedge leaf	$kg\ DM\ ha^{-1}\ d^{-1}$
GLVL	Growth rate of crop leaf lower alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GLVM	Growth rate of crop leaf middle alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GNGRNL	Growth number of grains in the lower alley	m^{-2}
GNGRNM	Growth number of grains in the middle alley	m^{-2}
GPHOTH	Daily total gross assimilation of the hedge	$kg\ CH_2O\ ha^{-1}\ d^{-1}$
GPHOTL	Daily total gross assimilation of the lower-alley crop	$kg\ CH_2O\ ha^{-1}\ d^{-1}$
GPHOTM	Daily total gross assimilation of the middle-alley crop	$kg\ CH_2O\ ha^{-1}\ d^{-1}$
GRDVS	Factor describing grain growth	-
GRDVST	Table of GRDVS as function of DVS	-
GRESH	Growth rate of hedge reserves	$kg\ DM\ ha^{-1}\ d^{-1}$
GRESL	Growth rate of crop reserves in the lower alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GRESM	Growth rate of crop reserves in the middle alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GRSINKL	Sink-determined growth rate of grains, lower alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GRSINKM	Sink-determined growth rate of grains, middle alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GRSOURL	Source-determined growth rate of grains, lower alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GRSOURM	Source-determined growth rate of grains, middle alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GRTH	Growth rate of hedge roots	$kg\ DM\ ha^{-1}\ d^{-1}$
GRTL	Growth rate of crop roots in the lower alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GRTM	Growth rate of crop roots in the middle alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GRTMP	Factor describing grain growth	-
GRTMPT	Table of GRTMP as function of DAVTMP	-
GSTH	Growth rate of hedge stem	$kg\ DM\ ha^{-1}\ d^{-1}$
GSTL	Growth rate of crop stem in the lower alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GSTM	Growth rate of crop stem in the middle alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GTWH	Growth rate of total hedge weight	$kg\ DM\ ha^{-1}\ d^{-1}$
GTWL	Growth rate of total crop weight in the lower alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GTWM	Growth rate of total crop weight in the middle alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GWLVLG	Growth of weight of green leaves in the lower alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GWLVMG	Growth of weight of green leaves in the middle alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GWRESL	Growth of weight of crop reserves in the lower alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GWRESM	Growth of weight of crop reserves in the middle alley	$kg\ DM\ ha^{-1}\ d^{-1}$
GZRTCF	Maximum growth rate of crop rooted depth	$mm\ d^{-1}$
GZRTH	Growth rate of hedge rooted depth	$mm\ d^{-1}$
GZRTHF	Maximum growth rate of hedge rooted depth	$mm\ d^{-1}$
GZRTL	Growth rate of crop rooted depth in the lower alley	$mm\ d^{-1}$
GZRTM	Growth rate of crop rooted depth in the middle alley	$mm\ d^{-1}$
HCEVH2-4	Conductivity per event layers 2-4 of hedgerow	mm
HCEVL2-4	Conductivity per event layers 2-4 of the lower-alley	mm
HCEVM2-4	Conductivity per event layers 2-4 of the middle-alley	mm
HCONH2-4	Hydraulic conductivity layers 2-4 of hedgerow	$mm\ d^{-1}$
HCONL2-4	Hydraulic conductivity layers 2-4 of the lower-alley	$mm\ d^{-1}$
HCONM2-4	Hydraulic conductivity layers 2-4 of the middle-alley	$mm\ d^{-1}$
HEDDIS	Distance between the hedgerows	m

HEDGE	Hedgerow width	m
HIC	Weighted harvest index of crop in the alley	-
HIL	Harvest index of crop in the lower alley	-
HIM	Harvest index of crop in the middle alley	-
HOFH	Horton overland flow from the hedge	mm
HOFL	Horton overland flow from the lower alley	mm
HOFM	Horton overland flow from the middle alley	mm
IMLCOV	Initial soil cover ratio of surface mulch	-
INFHED	Impact of the hedge on infiltration	-
INFMUL	Impact of mulch on infiltration	ha ^{1/2} t ^{1/2}
INFEVA	Infiltration during a rainfall event in the alley	mm
INFEVH	Infiltration during a rainfall event beneath the hedge	mm
INTC	Rainfall interception by the crop	mm d ⁻¹
INTH	Rainfall interception by the hedge	mm d ⁻¹
KDF	Extinction coefficient for plant leaves	-
LAICI	Initial crop leaf area index	-
LAIE	Leaf area index at emergence	-
LAIH	Leaf area index of the hedgerow	-
LAIHAP	Leaf area index of tree after pruning	-
LAIHI	Initial hedge leaf area index	-
LAIL	Leaf area index of the crop in the lower alley	-
LAIM	Leaf area index of the crop in the middle alley	-
LAT	Latitude of the site	degrees
LENGTH	Slope length	m
LHVAP	Latent heat of evaporation of water	J kg ⁻¹ K ⁻¹
LOWAL	Length of the zone designated to lower alley	m
MAINTH	Maintenance respiration rate of the hedge	kg CH ₂ O ha ⁻¹ d ⁻¹
MAINTL	Maintenance respiration rate of the lower-alley crop	kg CH ₂ O ha ⁻¹ d ⁻¹
MAINTM	Maintenance respiration rate of the middle-alley crop	kg CH ₂ O ha ⁻¹ d ⁻¹
MIDAL	Length of the zone designated to middle alley	m
MLCOV	Soil cover ratio of surface mulch	-
MLCOVT	Table of MLCOV and MULRT	-, t ha ⁻¹
MNDVSL	Effect of DVS on maintenance respiration, lower alley	-
MNDVSM	Effect of DVS on maintenance respiration, middle alley	-
MNTSH	Maintenance respiration rate of the hedge	kg CH ₂ O ha ⁻¹ d ⁻¹
MNTSL	Maintenance respiration rate of the lower-alley crop	kg CH ₂ O ha ⁻¹ d ⁻¹
MNTSM	Maintenance respiration rate of the middle-alley crop	kg CH ₂ O ha ⁻¹ d ⁻¹
MULCH	Amount of mulch still present in the soil	t ha ⁻¹
MULRT	Rate of mulch application	t ha ⁻¹
NCPL	Number of crop plants	m ⁻²
NDSLR	Number of days since last rain	-
NGA	Parameter in calculation of NGRain	-
NGB	Parameter in calculation of NGRain	-

NGRNL	Number of maize grains in the lower alley	m^{-2}
NGRNM	Number of maize grains in the middle alley	m^{-2}
NHPL	Number of hedge plants	m^{-2}
NRADH	Net radiation on the hedge	$\text{J m}^{-2} \text{d}^{-1}$
NRADL	Net radiation on the lower alley	$\text{J m}^{-2} \text{d}^{-1}$
NRADM	Net radiation on the middle alley	$\text{J m}^{-2} \text{d}^{-1}$
NRAINH	Net rainfall on the hedge	mm
NRAINL	Net rainfall on the lower alley	mm
NRAINM	Net rainfall on the middle alley	mm
OCLVDF	Old crop leaves decay factor	-
ORGCRB	Organic carbon content of the topsoil	-
PARTFH	Stress factor for hedge carbohydrate partitioning	-
PARTFL	Stress factor lower-alley crop carbohyd. partitioning	-
PARTFM	Stress factor middle-alley crop carbohyd. partitioning	-
PCLIH2-4	Percolation beneath the hedge into soil layer 2-4	mm
PCLIL2-4	Percolation in the lower alley into soil layer 2-4	mm
PCLIM2-4	Percolation in the middle alley into soil layer 2-4	mm
PCLOH2-4	Percolation beneath the hedge out of soil layer 2-4	mm
PCLOL2-4	Percolation in the lower alley out of soil layer 2-4	mm
PCLOM2-4	Percolation in the middle alley out of soil layer 2-4	mm
PDRAIN	Potential drainage	mm d^{-1}
PENMAH	Penman's value for potential hedge evaporation	mm d^{-1}
PENMAL	Penman's value for evaporation from the lower alley	mm d^{-1}
PENMAM	Penman's value for evaporation from the middle alley	mm d^{-1}
PEVAPH	Potential evaporation from the hedge	mm d^{-1}
PEVAPL	Potential evaporation from the lower alley	mm d^{-1}
PEVAPM	Potential evaporation from the middle alley	mm d^{-1}
PGRI	Potential growth rate of grains	$\text{mg DM grain}^{-1} \text{d}^{-1}$
PI	Ratio of circumference to diameter of circle	-
PINFH	Potential infiltration beneath the hedge	mm
PINFL	Potential infiltration in the lower alley	mm
PINFM	Potential infiltration in the middle alley	mm
PKRWT	Potential kernel weight	mg DM grain^{-1}
POFH	Potential overland flow from the hedge	mm
POFL	Potential overland flow from the lower alley	mm
POFM	Potential overland flow from the middle alley	mm
PRAIN	Total rainfall from the preceding season	-
PREINF	Total water infiltrated preceding a storm	mm
PRIN	Subroutine that calculates PREINF	-,mm
PRODFH	Stress factor for hedge carbohydrate production	-
PRODFL	Stress factor for lower-alley crop CH_2O production	-
PRODFM	Stress factor for middle-alley crop CH_2O production	-
PSYCH	Psychrometer constant	kPa K^{-1}
PTRNSH	Potential hedge transpiration	mm d^{-1}
PTRNSL	Potential crop transpiration in the lower alley	mm d^{-1}
PTRNSM	Potential crop transpiration in the middle alley	mm d^{-1}

Q10	Temperature dependency of maintenance respiration	-
RADIAT	Subroutine that calculates instant radiation above canopy	-
RAIN	Daily rainfall	mm d ⁻¹
RDD	Total daily global radiation	J m ⁻² d ⁻¹
RDFRLH	Reduction of hedge assimilation if reserves are present	-
RDFRLL	Reduction of crop assimilation in the lower alley	-
RDFRLM	Reduction of crop assimilation in the middle alley	-
RDR	Relative death rate of leaves	d ⁻¹
RESLH	Fraction of reserves/weight of hedge stem	-
RESLL	Fraction of reserves/weight of lower-alley crop-stem	-
RESLM	Fraction of reserves/weight of middle-alley crop-stem	-
RESLMXC	Maximum allowable RESLL or RESLM for crops	-
RESLMXH	Maximum allowable RESLH for hedges	-
RFDUR	Duration of rainfall event	h
RFDURT	Table of RFDUR and Julian days	h, d
RFINAW	Average intensity of rainfall in the period after weeding	mm h ⁻¹
RFINT	Average intensity of rainfall	mm h ⁻¹
RGRL	Relative growth rate of leaves per degree-day	°C ⁻¹ d ⁻¹
RLWN	Net long wave radiation	J m ⁻² d ⁻¹
RNOFFH	Runoff from the hedge	mm d ⁻¹
RNOFFL	Runoff from the lower alley	mm d ⁻¹
RNOFFM	Runoff from the middle alley	mm d ⁻¹
RRAIN	Daily rainfall	mm d ⁻¹
RUNOFF	Total runoff from the hedgerow barrier system	mm d ⁻¹
RUNONH	Total amount of surface water entering the hedgerow	mm
RUNONL	Total amount of surface water entering the lower alley	mm
RWCLH1-4	Relative water content beneath the hedge soil layer 1-4	-
RWCLL1-4	Relative water content in the lower-alley soil layer 1-4	-
RWCLM1-4	Relative water content in the middle-alley soil layer 1-4	-
SAND	Percentage sand in topsoil	-
SATDEF	Saturated vapour pressure deficit	kPa
SATFAC	Soil water saturation factor of the topsoil	-
SCP	Scattering coefficient of leaves for PAR	-
SDRY	Drought stress sensitivity coefficient	-
SEDCON	Sediment concentration in runoff	kg m ⁻³
SHPRUN	Biomass production of single-row hedges	t ha ⁻¹
SILT	Percentage silt in topsoil	-
SL	Slope angle of the site	radians
SLAC	Specific leaf area of the crop	ha kg ⁻¹
SLOPE	Slope angle of the site	degrees
SLOSSH	Soil loss from the hedgerow system without mulching	t ha ⁻¹
SLOSSM	Soil loss from the hedgerow system with mulching	t ha ⁻¹
SLOSS	Soil loss from the hedgerow barrier system	t ha ⁻¹
SOLCOV	Total soil cover	-
SOF1-4	Saturation overland flow	mm
SORPH	Topsoil water deficit under the hedge	-

SORPL	Topsoil water deficit in the lower-alley	-
SORPM	Topsoil water deficit in the middle-alley	-
STFLH1-4	Upward-directed flow beneath the hedge soil layer 1-4	mm
STFL1-4	Upward-directed flow in the lower-alley soil layer 1-4	mm
STFLM1-4	Upward-directed flow in the middle-alley soil layer 1-4	mm
SVP	Saturated vapour pressure	kPa
SWET	Flooding stress sensitivity coefficient	-
TADRWC	Total above-ground crop dry matter	kg DM ha ⁻¹
TADRWH	Total above-ground hedge dry matter	kg DM ha ⁻¹
TADRWL	Total above-ground crop dry matter in the lower alley	kg DM ha ⁻¹
TADRWM	Total above-ground crop dry matter in the middle alley	kg DM ha ⁻¹
TAEVPH	Total actual evaporation beneath the hedge	mm
TAEVPL	Total actual evaporation in the lower alley	mm
TAEVPM	Total actual evaporation in the middle alley	mm
TAINFH	Total actual infiltration beneath the hedge	mm
TAINFL	Total actual infiltration in the lower alley	mm
TAINFM	Total actual infiltration in the middle alley	mm
TAINTH	Total actual rainfall interception of the hedge	mm
TAINTL	Total actual rainfall interception in the lower alley	mm
TAINTM	Total actual rainfall interception in the middle alley	mm
TATRNH	Total amount of water transpired by the hedgerow	mm
TATRNL	Total water transpired by the lower-alley crop	mm
TATRNM	Total water transpired by the middle- alley crop	mm
TBASE	Base temperature for juvenile leaf growth	°C ⁻¹
TC	Time constant in utilizing reserves	d ⁻¹
TCOB	Total cob weight	kg DM ha ⁻¹
TCOBL	Total cob weight of the lower alley	kg DM ha ⁻¹
TCOBM	Total cob weight of the middle alley	kg DM ha ⁻¹
TDECAW	Total decline of surface storage after weeding	mm
TDECFW	Total decline of surface storage after first weeding	mm
TDECLF	Cumulative decline factor of surface depressions	-
TDECSW	Total decline of surface storage after second weeding	mm
TDPWTH	Total water stored in depressions beneath the hedge	mm
TDPWTL	Total water stored in depressions in the lower alley	mm
TDPWTM	Total water stored in depressions in the middle alley	mm
TDRAIN	Total drainage	mm
TDRNH	Total drainage beneath the hedgerow	mm
TDRNL	Total drainage in the lower alley	mm
TDRNM	Total drainage in the middle alley	mm
TDRWH	Total hedge dry weight	kg DM ha ⁻¹
TDRWL	Total crop dry weight in the lower alley	kg DM ha ⁻¹
TDRWM	Total crop dry weight in the middle alley	kg DM ha ⁻¹
TEFF	Temperature effect on maintenance respiration	-
TEVAPD	Total potential evaporation due to dry air	mm
TEVPRH	Total potential evaporation due to radiation, the hedge	mm
TEVPRL	Total potential evaporation due to radiation, lower alley	mm
TEVPRM	Total potential evaporation due to radiation, middle alley	mm

TEXTUR	Sensitivity of the topsoil to erosion due to texture	-
THOFH	Total Horton overland flow from the hedge	mm
THOFL	Total Horton overland flow from the lower alley	mm
THOFM	Total Horton overland flow from the middle alley	mm
TKLT	Total thickness of soil layers	mm
TKL1-4	Thickness of soil layer 1-4	mm
TLAIH	Total leaf area index of the hedgerow	-
TLAIL	Total leaf area index of the crop in the lower alley	-
TLAIM	Total leaf area index of the crop in the middle alley	-
TMMN	Daily minimum temperature	°C
TMMX	Daily maximum temperature	°C
TPEVPH	Total potential evaporation beneath the hedge	mm
TPEVPL	Total potential evaporation in the lower alley	mm
TPEVPM	Total potential evaporation in the middle alley	mm
TPTRNH	Total potential transpiration from the hedge	mm
TPTRNL	Total crop potential transpiration in the lower alley	mm
TPTRNM	Total crop potential transpiration in the middle alley	mm
TRAIN	Total rainfall	mm
TRNOFH	Total runoff from the hedgerow	mm
TRNOFL	Total runoff from the lower alley	mm
TRNOFM	Total runoff from the middle alley	mm
TRRMH	Potential hedge transpiration rate per mm rooted depth	mm ⁻¹
TRRML	Potential crop transpiration rate per mm rooted depth	mm ⁻¹
TRRMM	Potential crop transpiration rate per mm rooted depth	mm ⁻¹
TRROWS	Number of tree rows in one hedgerow barrier	-
TRWLH1-4	Rate of hedge transpiration from soil layer 1-4	mm d ⁻¹
TRWLL1-4	Crop transpiration rate in the lower-alley soil layer 1-4	mm d ⁻¹
TRWLM1-4	Crop transpiration rate in the middle-alley soil layer 1-4	mm d ⁻¹
TSLOSS	Total soil loss from the hedgerow barrier system	t ha ⁻¹
TSOFH	Total saturation overland flow from the hedgerow	mm
TSOFL	Total saturation overland flow from the lower alley	mm
TSOFM	Total saturation overland flow from the middle alley	mm
TSUMEM	Total temperature above TBASE	°C d
VP	Actual vapour pressure	kPa
WCADH1-4	Water content of air dry soil beneath hedge layer 1-4	-
WCADL1-4	Water content of air dry soil in lower-alley layer 1-4	-
WCADM1-4	Water content of air dry soil in middle-alley layer 1-4	-
WCFCH1-4	Field capacity beneath the hedge soil layer 1-4	-
WCFCL1-4	Field capacity in the lower-alley soil layer 1-4	-
WCFCM1-4	Field capacity in the middle-alley soil layer 1-4	-
WCHL	Weight of chaff in the lower alley	kg DM ha ⁻¹
WCHM	Weight of chaff in the middle alley	kg DM ha ⁻¹
WCLH1-4	Water content beneath the hedge in soil layer 1-4	-
WCLH11-4	Initial water content beneath the hedge in soil layer 1-4	-
WCLL1-4	Water content in the lower alley in soil layer 1-4	-
WCLLI1-4	Initial water content in the lower alley in soil layer 1-4	-

WCLM1-4	Water content in the middle alley in soil layer 1-4	-
WCLMI1-4	Initial water content in the middle alley in soil layer 1-4	-
WCSTH1-4	Saturation in the hedge in soil layer 1-4	-
WCSTL1-4	Saturation in the lower-alley in soil layer 1-4	-
WCSTM1-4	Saturation in the middle alley in soil layer 1-4	-
WCUMH	Total amount of water in soil profile beneath the hedge	mm
WCUMHI	Total initial amount of water beneath the hedge	mm
WCUML	Total amount of water in soil profile in the lower alley	mm
WCUMLI	Total initial amount of water in the lower alley	mm
WCUMM	Total amount of water in soil profile in the middle alley	mm
WCUMMI	Total initial amount of water in the middle alley	mm
WCWPH1-4	Wilting point beneath the hedge in soil layer 1-4	-
WCWPL1-4	Wilting point in the lower alley in soil layer 1-4	-
WCWPM1-4	Wilting point in the middle alley in soil layer 1-4	-
WDF	Wind function	mm d ⁻¹ kPa ⁻¹
WGRAIN	Weight of grains	kg DM ha ⁻¹
WGRNL	Weight of grains in the lower alley	kg DM ha ⁻¹
WGRNM	Weight of grains in the middle alley	kg DM ha ⁻¹
WLH1-4	Amount of water beneath the hedge in soil layer 1-4	mm
WLH1I-4I	Initial amount of water beneath the hedge soil layer 1-4	mm
WLL1-4	Amount of water in the lower alley soil layer 1-4	mm
WLL1I-4I	Initial amount of water in the lower-alley soil layer 1-4	mm
WLM1-4	Amount of water in the middle alley soil layer 1-4	mm
WLM1I-4I	Initial amount of water in the middle-alley soil layer 1-4	mm
WLVC1	Weight of crop leaves at emergence	kg DM ha ⁻¹
WLVIH	Weight of hedge leaves	kg DM ha ⁻¹
WLVIH1	Weight of hedge leaves after pruning	kg DM ha ⁻¹
WLVL	Weight of crop leaves in the lower alley	kg DM ha ⁻¹
WLVL1	Weight of dead crop leaves in the lower alley	kg DM ha ⁻¹
WLVLG	Weight of green crop leaves in the lower alley	kg DM ha ⁻¹
WLVM	Weight of crop leaves in the middle alley	kg DM ha ⁻¹
WLVM1	Weight of dead crop leaves in the middle alley	kg DM ha ⁻¹
WLVMG	Weight of green crop leaves in the middle alley	kg DM ha ⁻¹
WN	Wind speed	m s ⁻¹
WRESH	Weight of hedge reserves	kg DM ha ⁻¹
WRESL	Weight of crop reserves in the lower alley	kg DM ha ⁻¹
WRESM	Weight of crop reserves in the middle alley	kg DM ha ⁻¹
WRTCI	Weight of roots at emergence	kg DM ha ⁻¹
WRTH	Weight of hedge roots	kg DM ha ⁻¹
WRTH1	Weight of roots after pruning	kg DM ha ⁻¹
WRTL	Weight of crop roots in the lower alley	kg DM ha ⁻¹
WRTM	Weight of crop roots in the middle alley	kg DM ha ⁻¹
WSEH1-4	Water stress effect beneath the hedge in soil layer 1-4	-
WSEL1-4	Water stress effect in the lower alley in soil layer 1-4	-
WSEM1-4	Water stress effect in the middle alley in soil layer 1-4	-
WSERH1-3	Water stress effect on hedge root extension	-
WSERL1-3	Water stress effect on lower-alley crop root extension	-
WSERM1-3	Water stress effect on middle-alley crop root extension	-

WSTH	Weight of hedge stem	kg DM ha ⁻¹
WSTHI	Initial weight of hedge stem	kg DM ha ⁻¹
WSTL	Weight of crop stem in the lower alley	kg DM ha ⁻¹
WSTM	Weight of crop stem in the middle alley	kg DM ha ⁻¹
WSTOV	Weight of stover in the alley	kg DM ha ⁻¹
WSTOVL	Weight of stover in the lower alley	kg DM ha ⁻¹
WSTOVM	Weight of stover in the middle alley	kg DM ha ⁻¹
ZEFSOR	Depth of effective soil moisture deficit	mm
ZDPFWI	Initial depth surface depression after first weeding	mm
ZDPR	Depth surface depression	mm
ZDPRAP	Depth surface depression after planting	mm
ZDPRAW	Depth surface depression after weeding	mm
ZDPRFW	Depth surface depression after first weeding	mm
ZDPRPI	Initial depth surface depression after planting	mm
ZDPRSW	Depth surface depression after second weeding	mm
ZDPRWI	Initial depth surface depression after weeding	mm
ZDPSWI	Initial depth surface depression after second weeding	mm
ZRTCI	Initial crop rooted depth	mm
ZRTH	Rooted depth of hedge	mm
ZRTH1-4	Rooted depth of hedge in soil layer 1-4	mm
ZRTHI	Initial hedge rooted depth	mm
ZRTL	Rooted depth of crop in the lower alley	mm
ZRTL1-4	Rooted depth of crop in the lower-alley soil layer 1-4	mm
ZRTM	Rooted depth of crop in the middle alley	mm
ZRTM1-4	Rooted depth of crop in the middle-alley soil layer 1-4	mm
ZRTMC	Maximum value of rooted depth by crop characteristics	mm
ZRTMS	Maximum value of rooted depth by soil characteristics	mm
ZRTMX	Maximum value of rooted depth	mm

Curriculum Vitae

Paul Kiepe was born on 21 May 1955 in Surabaya, Indonesia. He graduated from HBS-B at Beverwijk in June 1972, after which he studied for two years Mathematics & Physics at the University of Amsterdam. Getting extremely bored, he decided to go to Wageningen Agricultural University in September 1974, where he graduated for his B.Sc. in January 1979. He worked four months at the Research Institute for Nature Management at Arnhem, The Netherlands, for his practical experience, as well as eight months in Tai National Park, Ivory Coast. Field work for his first M.Sc. thesis took him for four months to Parc National Boucle du Baoulé, Mali, where he looked into the relation between soils and vegetation of abandoned termite mounds. Field work for his second M.Sc. thesis took him for three months to Kasserine, Tunisia, where he carried out a soil and vegetation survey, and, subsequently, a land evaluation. Despite the exotic topic 'Water and nutrient cycling in tropical rainforests' his third M.Sc. thesis was accomplished in Wageningen. He graduated for his M.Sc. in September 1984. After working as guest researcher at ISRIC, Wageningen, he joined the Ministry for Development Cooperation for six months in May 1987. He left for Kenya in December 1987, where he joined ICRAF to study the effect of trees on soil and water conservation. He returned in November 1992, to join the Department of Irrigation and Soil & Water Conservation of Wageningen Agricultural University as a visiting scientist for six months. From May 1993 onwards he worked for two years on his Ph.D.

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Six books were of specific guidance during this study and should be mentioned here: Soil Conservation (1986) by Norman Hudson, Soil Erosion Research Methods (1988) by Ratan Lal, Hillslope Hydrology (1988) by Michael Kirkby, Applied Hydrology (1988) by Ven Te Chow, Applications of Soil Physics (1980) by Daniel Hillel and, of course, Agroforestry for Soil Conservation (1989) by Anthony Young. I thank Tony for the many things he taught me, his continuous support, his witty remarks and his excellent company on our field trips. Field experiments were conducted at the Machakos Research Station of the International Centre for Research in Agroforestry (ICRAF). Special thanks, in many ways, to the Scientific Coordinator of Machakos Research Station and Leader of the Components Interaction Programme, M.R. Rao. I thank Imke van der Meer and Gilbert Mwasambu for carrying out part of the infiltration studies. Thanks to Peter Kurira for the excellent management of the Research Station, to Muthoka Mailu for incorporating meteorological data into Fortran data files and to Mwasambu, again, for taking good care of my trials. I thank Mirjam Njoroge for her backup support with various data files, after I had left Kenya.

Measurements of hydraulic conductivity and soil water characteristics were carried out at the Soil Physics Laboratory of the Wageningen Agricultural University (WAU). I thank Wil Ackerman for his help in the laboratory.

The first computer simulation model that I wrote in PCSMP at Wageningen, called PSYCHIC (Process Simulation of Yields in Contour Hedgerow InterCropping) was merely an extended crop growth model, but already capable to set my research agenda. Its successor, called CHAOS (Contour Hedgerow Arrangements On Slopes), was a runoff model, which was also written in PCSMP, this time in Nairobi. Finally, the model was expanded in Wageningen with various modules and a soil loss balance, translated into FST and renamed to SHIELD (Simulation of Hedgerow Intervention against Erosion and Land Degradation)¹. I thank Gon van Laar (Dept. of Theoretical Production Ecology of Wageningen Agricultural University) and Kees Rappoldt (AB-DLO, Haren) for their help and ideas.

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¹SHIELD supersedes PSYCHIC and CHAOS